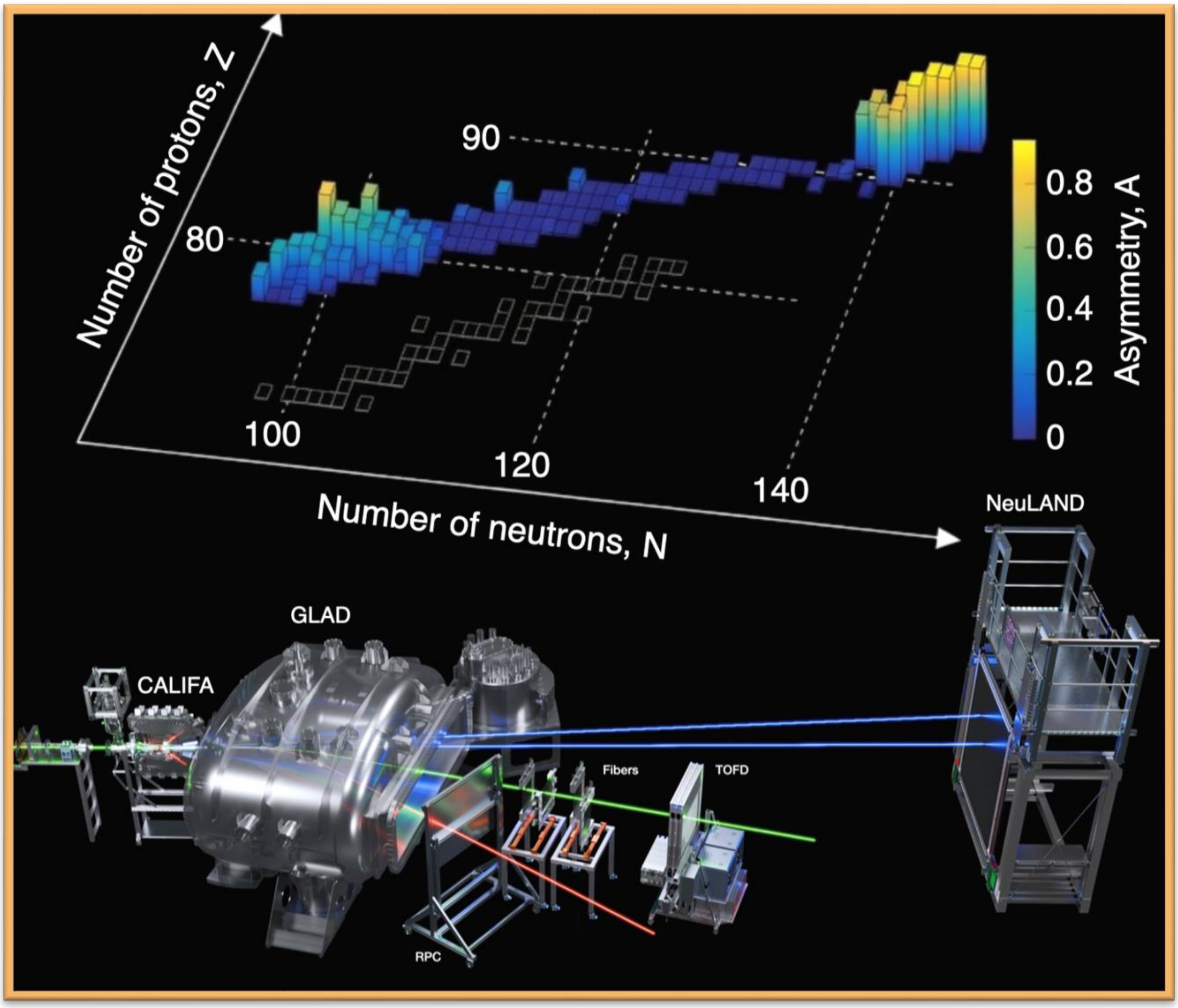
GSI REPORT 2026-1

GSI-FAIR SCIENTIFIC REPORT 2025

An overview of the 2025 achievements in science and technology



Cover page illustration:
Top: Discovery of an “asymmetric fission island” in neutron-deficient nuclei (Nature 641, 2025) using the R3B setup at GSI Helmholtzzentrum für Schwerionenforschung GmbH. Atomic nuclei are defined by their numbers of neutrons and protons. In the figure, the investigated nuclei are highlighted in colour, while naturally occurring stable isotopes are shown in black. The colour scale further illustrates the fission behaviour: the taller the column, the greater the mass asymmetry between the two fission fragments. Image credit: Pierre Morfouace.
Bottom: 3D rendering of the R3B setup for the G-24-00249 experiment in 2025. Illustration by Valerii Panin.

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Imprint

Published and printed by
GSI Helmholtzzentrum für Schwerionenforschung GmbH,
Planckstr. 1, 64291 Darmstadt, Germany

Editors: Arnaud Le Fèvre, Yvonne Leifels.

Publication date: May 2026
GSI Report 2026-1, DOI: 10.15120/GSI-2026-00627, license: ccby4
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Contents

1. Executive summary of research at GSI & FAIR

Coordination: Dr. Yvonne Leifels (GSI)

1.1 Research and technical developments at GSI/FAIR

Author: Yvonne Leifels.

2025 was a very successful year. The Research Division of GSI and FAIR achieved significant operational milestones, received top-tier institutional ratings, and made substantial progress in constructing the components for the FAIR 2028 operational scenario.

The scientific evaluation of the GSI Helmholtzzentrum, conducted in April 2025, was a critical milestone in the Program Oriented Funding process. The evaluation was designed as a comprehensive review of GSI's scientific performance during the first half of the PoF IV period (2021-2024). An international board of 19 experts conducted the review, chaired by Prof. Patricia Rossi, a nuclear physicist from Jefferson Laboratory. The review was based on two volumes of documentation: Volume 1 focused on the research topics and programs, while Volume 2 described performance indicators, resources, and the curricula vitae of the principal investigators. A six-day onsite review (April 6-11) included tours of the GSI facilities and the FAIR construction site. It also covered the Helmholtz Institutes in Mainz (via an on-site visit) and Jena (via virtual tours and a poster session after a last-minute cancellation of the physical visit). In May 2025, the evaluation report was issued and it concludes that the centre demonstrates strong scientific performance and serves as an important contributor to the Helmholtz Association's MATTER research field. The evaluation committee assigned "Outstanding" and "Excellent" ratings across nearly all research topics for scientific achievements and international standing.

The centre's scientific work is divided into three primary programs, all showing significant international impact:

Matter and the Universe (MU): The contributions focus on strongly interacting and multi-body systems. Key highlights include the breakthrough research on exotic nuclei, the first observation of the ^{28}O isotope, and the observation of the bound state beta decay of ^{205}Tl, which helped to constrain the time for the formation of the solar system.

Matter and Technologies (MT): This program successfully provides the tools for cutting-edge research. Highlights include the successful development and testing of the HELIAC cryomodule, upgrade of the ALICE TPC detector and the development of energy-efficient AI-driven job scheduling in the Green IT Cube.

From Matter to Materials and Life (MML): This program profits from the unique capabilities of the heavy ion accelerators at GSI. Main achievements are achieved precision tests of strong-field QED and research on nuclear clocks. Materials research provides an adaptable platform for ion track nanotechnology and materials testing in extreme environments. Biophysics at GSI is recognised as world leader in innovative ion beam therapy for cancer and research into health effects for long-duration human spaceflight.

Despite the high ratings, the committee also identified several critical areas for improvement. The accelerator complex requires substantial upgrades to ensure high availability for the FAIR facility. In addition, increased staffing in Detector Technologies (DTS) and ASIC development is needed to broaden the expertise portfolio. Furthermore, to remain competitive in high-energy-density science, expanded high-power laser capabilities are necessary.

The focus of GSI research is primarily defined by the transition to the FAIR2028 operational scenario: the gradual completion and start of operation of the core components of the Facility for Antiproton and Ion Research (FAIR). By the end of 2027, it is planned to start commissioning of the Super-FRS (including its High-Energy Branch) and have the SIS100 synchrotron operational by 2028. By 2028, the scientific opportunities comprise the CBM and NUSTAR facilities in the High-Energy Branch and numerous facilities at GSI. These facilities will enable unprecedented research in hadron physics using proton beams at CBM, as well as nuclear physics utilizing high-energy exotic beams from the Super-FRS and high-intensity heavy-ion beams. Materials science and Biophysics will make use of SIS100 beams and the existing GSI facilities at SIS18 and UNILAC, atomic physics experiments will concentrate on the storage rings, ESR and CRYRING, and SIS100, where the plasma physics aims towards a stepwise enhancement of the high-power laser facilities of laser fusion research with the final goal to set-up a high-power laser facility close to the APPA cave at FAIR.

In 2025, GSI and FAIR convened several **Program Advisory Committees (PACs)** to evaluate and prioritize experiment proposals for the upcoming 2026–2027 beamtime periods. These international expert panels advise the GSI Management Board on selecting scientifically excellent projects, a task made particularly difficult by the reduced beamtime availability caused by FAIR accelerator commissioning and campus refurbishment.

The 46th **G-PAC** meeting took place from February 18–20 for the evaluation of 57 scientific proposals and 13 proposals for detector tests, requesting a total of 2,365 shifts. The committee allocated 186 shifts for UNILAC, 201 for SIS18/FRS, and 253.5 for storage rings (ESR, CRYRING, and HITRAP). Because available time was substantially reduced compared to previous years, overbooking factors were extremely high, reaching 4.4 for the ESR.

The 19th **PPAC** meeting was held on January 23–24, 2025. With 20 submitted proposals, there was a significant rise from the 14 submitted in 2022. The committee granted 126 shifts for the PHELIX laser and approximately 84 shifts at the SIS18.

The **Bio-PAC** evaluated proposals between June 30th and July 1st. The committee approved 9 experiments with priority A (granted) and 6 with A- (reserve). The Priority A experiments represent 60 shifts over two years, with an overbooking factor of 1.8.

The **Mat-PAC** met on June 16–17, 2025. The call aimed to allocate 87 shifts at UNILAC, 30 shifts at SIS18, and 10 shifts at the storage rings for the 2026–2027 period.

The 2025 **beamtime** at GSI/FAIR was characterised as "extremely successful," setting several operational records and delivering a highly productive scientific program that ran from February to the beginning of July 2025.

- Highest Reliability: The beam-operation time reached levels not seen since 2014.
- Minimal Downtime: Technical interruptions were reduced to below 10%, a record for the facility while running the full accelerator complex.
- Facility Usage: Accountable days for the year included 120 days for SIS18, 122 days for the ESR, and 16 days for CRYRING.

Scientific Highlights by the experimental facilities are:

- HADES Spectrometer: Following a successful repair of its cryogenic system in April, HADES completed a compensation run studying the reaction Au+Au at various energies. Combined with 2024 data, it recorded 5.9 billion events in just 11 days—effectively doubling its data collection rate due to upgraded front-end electronics and a novel beam feed-back system to optimize the macro- and micro spill structure of the beam.
- CRYRING@ESR: A major milestone was the successful storage and cooling of an intense deuterium beam at 90 keV/u, the lowest energy ever achieved at the facility, used to study reactions relevant to Big Bang nucleosynthesis
- HITRAP: In March 2025, the facility conducted its first official user experiment, using decelerated Au79+ ions to investigate the nanostructuring of monolayer graphene.
- SHIP and FRS: The SHIP separator operated for the first time with entirely new power supplies, improving reliability, and at the FRS, the LISA active target for HISPEC experiments was successfully commissioned in May 2025
- PHELIX Laser: The program focused on combined laser-ion experiments at the HHT and Z6 target stations. A highlight was the investigation of laser-plasma instabilities using a new broadband laser front-end and a unique 20-cm DKDP crystal.
- mCBM: The PANDA collaboration successfully participated in mCBM beamtimes in February, testing straw detector modules integrated into the mCBM setup and data acquisition system.

An **evaluation of the Hesse Centre for FAIR (HFHF)** was conducted by an international panel in October 2025 to assess the program's achievements between 2021 and 2025 and its future potential. The panel concluded that HFHF is successfully delivering on its mission to focus the expertise of Hesse Universities and FIAS toward research at the FAIR. In particular, the panel was impressed by the research quality. HFHF funding currently supports 9 postdoctoral fellows and 30 graduate students, playing a critical role in training the next generation of scientific leaders for FAIR. In addition, HFHF researchers have made substantial contributions to the construction of FAIR experiments, including detector developments for CBM and innovations in accelerator technology, such as 3D-printed copper components.

The Summer Student Program integrated 34 students from 11 countries directly into the 2025 research activities, including testing components for future FAIR experiments.

In 2025, GSI Helmholtzzentrum für Schwerionenforschung and its scientists received several prestigious international prizes, major research grants, and high-level appointments.

- Breakthrough Prize in Physics: This $3 million prize was awarded to the four large LHC collaborations at CERN, including ALICE, for their fundamental discoveries and exploration of nature at extreme conditions. GSI plays a decisive role in the ALICE collaboration, having built key components like the Time Projection Chamber.
- Slovakian Order Ľudovít Štúr: Prof. Livia Ludhova, head of the joint neutrino group at GSI, was honoured on January 11, 2025, with the 2nd Class, Civil Division order for her exceptional contributions to science and technology.
- BIR Medal: Prof. Marco Durante, Head of the Biophysics Department, was awarded the "BIR Medal for Outstanding International Achievement 2024" by the British Institute of Radiology for his transformative achievements in radiation oncology.
- ERC Advanced Grant: Prof. Marco Durante was awarded a second ERC Advanced Grant for the "Heavy-Ion FLASH" project, which aims to use ultra-high dose rates of neon ions to treat resistant tumours.
- ERC Consolidator Grant: Dr. Christoph Heyl of the Helmholtz Institute Jena received this grant for the "GASONIC" project to research gas phase sonophotonics.
- BMFTR Fusion Talents: Jonas Ohland received a personal grant of approximately €2.8 million for the "ALADIN" project to develop laser beam control for fusion power plants.
- University Excellence Grant: Bonn University received funding that includes support for the INSIGHT experiment, which incorporates the PANDA Forward Endcap.
- ALICE Collaboration Spokesperson: Dr. Kai Schweda was elected as the spokesperson for the global ALICE collaboration at CERN, with his three-year term beginning in 2026.
- AGATA Steering Committee Chair: Dr. Magdalena Gorska was elected to chair this international committee.
- Professorial Appointments: Dr. Kathrin Wimmer accepted a W3 professorship at the University of Cologne, and Dr. Johan Messchendorp received an offer for a W2 professorship at the University of Bochum.

In summary, 2025 was a highly productive year for the GSI research division, marked in particular by an extremely successful beam time and strong scientific output across all research activities, combined with excellent evaluation results, highlights the robustness of the research activities and infrastructure. While important challenges remain — especially the transition of major projects into their operational phases towards the FAIR 2028 scenario — the overall progress provides a solid foundation for the next stages of FAIR commissioning and future scientific exploitation.

Outlook 2026

In 2026, research at GSI will be strongly influenced by the consequences of the fire incident beginning of February 2026, which originated in the RF supply section of the UNILAC and destroyed critical infrastructures. The full extent of the damage has not yet been fully assessed, but a prolonged interruption of operation is expected. Now the priorities lie on the rapid recovery of the scientific opportunities at GSI by assessing and fast repair of the damaged infrastructures. However, it became clear quite fast that the longpulse operation of the UNILAC cannot be restored. Measures are planned which will ensure that the start of commissioning of the FAIR accelerators, Super-FRS and SIS100, will be possible according to the original schedule, allow first scientific experiments at FAIR and enable partial resumption of experimental activities at the GSI facilities. Therefore, the continued development of FAIR remains of central importance, with further progress in construction and commissioning and the integration of new experimental user communities.

The fire also highlights the importance of strategic infrastructure development. In this context, the HELIAC accelerator will be key for restoring and extending long-pulse operation in a more energy-efficient way. Advancing HELIAC — through securing funding and prioritization — will be another important goal for 2026.

Overall, 2026 will be a year of managing challenges and taking focused actions. Together, we will keep research at GSI and FAIR on track and moving forward.

1.2 Beamtimes for scientific experiments in 2025

Author: Daniel Severin

Proposal number	Experiment topic	Spokesperson	Main shifts	Parasitic shifts
B-Barb	Biophysics with FRS-HTM beam	Durante, Marco	6	
B-Bio	Biophysics at SIS18 (incl. Radnext)	Durante, Marco	15	
B-Dual beam	Biophysics with Dual-beam	Graeff, Christian	10	
B-ESA	ESA beamtime	Durante, Marco	0	
B-U Bio	Biophysics at UNILAC	Durante, Marco	3	
G-22-00018	Nuclear two-photon decay and bound-state pair conversion	Korten, Wolfram	19	
G-22-00022	Searching for critical behavior and limitations of the universal Freeze-out line	Stroth, Joachim	54	
G-22-00027	Neutron skin measurement of ^{132}Sn and ^{144}Xe	Kanungo, Rituparna	28	
G-22-00038	Continuation of E128 Dielectronic Recombination-assisted laser spectroscopy: A new tool to investigate the hyperfine-puzzle in $Bi^{80+,82+}$	Nörtershäuser, Wilfried	22	
G-22-00040	Exploring the fission, beta decay and α-decay fine structure of superheavy nuclei with ANSWERS at TASCA	Jadambaa, Khuyagbaatar	35	31
G-22-00051	Laser spectroscopy of californium, fermium, nobelium and lawrencium isotopes around N=152	Raeder, Sebastian		37
G-22-00052	Follow-Up E142: Laser Excitation of the ^{229}Th Nucleus Using Nuclear Hyperfine Mixing	Brandau, Carsten	22	
G-22-00056	Nuclear symmetries and structure studies via mass measurements at the N=Z line from Ge to Rh	Plaß, Wolfgang	36	
G-22-00057	Nanostructuring of monolayer graphene by highly charged ions	Niggas, Anna		7
G-22-00072	Commissioning and First Storage Ring Experiments of the CRYRING Transverse Electron Target (Resubmission of Proposal E149)	Brandau, Carsten	21	
G-22-00075	Laser spectroscopy of the (1s2 2s2p) 3P0 - 3P1 level splitting in Be-like krypton (This is a resubmission of E135)	Winters, Danyal	20	
G-22-00092	Testing diamond detectors for development of an active target	Wimmer, Kathrin	7	
G-22-00103	Test of the beam tracking and identification for HISPEC-10	Vesic, Jelena	16	
G-22-00110	mCBM SIS18 2023/24	Sturm, Christian	27	
G-22-00111	Towards limits of nuclear structure by using a ^{9}C beam	Chudoba, Vratislav	14	50
G-22-00115	Study of a nuclear sandbank at the proton unbound bromine isotopes	Pfutzner, Marek		4
G-22-00122	Symmetry energy at high densities from neutron/proton flow excitation functions	Russotto, Paolo	13	

Proposal number	Experiment topic	Spokesperson	Main shifts	Parasitic shifts
G-22-00134	Precision x-ray spectroscopy of helium-like uranium using metallic magnetic calorimeter detectors	Weber, Günter	7	
G-22-00143	Test of DESPEC Fibre Implanter (FIMP)	Vencelj, Matjaz	29	14
G-22-00150	Mass measurements at N≈126 for understanding the 3rd r-process abundance peak	Scheidenberger, Christoph	7	
G-22-00154	Probing with high accuracy the atomic mass of superheavy elements and the excitation energy of their low-lying isomeric states with SHIPTRAP	Giacoppo, Francesca	12	
G-22-00160	FRS developments for APPA and NUSTAR experiments: Performance improvements and R&D work with heavy-ion beams	Scheidenberger, Christoph		2
G-22-00174	In-beam test of a TOF-DE-E method for complete identification via mass-(A) and charge-(Z) number of fragments produced in Multi Nucleon Transfer reactions	Vardaci, Emanuele	9	
G-22-00182	Fission isomer studies with the FRS	Zhao, Jianwei	26	
G-22-00203	Mass & half-life measurements in the neutron-rich N≈116 Hf region	Litvinov, Yuri	6	7
G-22-00204/UR	Dielectronic Recombination of 19F6+ as a benchmark for the CRYRING@ESR electron cooler in internal target mode	Krantz, Claude	28	
G-22-00205/UR	Measurement of the 7Li(p,n)7Be reaction using CARME@CRYRING	Marsh, Jordan	63	95
G-22-00206/UR	Investigation of D+D fusion at BBN energies using CARME@CRYRING	Bruno, Carlo	102	30
G-24-00210/UR	Absolute rate coefficients from dielectronic recombination for the astrophysically relevant ion O2+	Hanu, Elena-Oana	20	
M-CMAT	Materials Research at Cryring	Toimil-Molares, Maria Eugenia	11	
M-SMAT	Materials Research at SIS18	Toimil-Molares, Maria Eugenia	19	
M-UMAT	Materials Research at UNILAC	Toimil-Molares, Maria Eugenia	22	
P-22-00125	Detection of ion-beam heating induced melting and graphitization by laser-driven x-ray probing	Major, Zsuzsanna	15	
T-SFRS Det. Tests	Super-FRS Detector tests	Simon, Haik		6
G-24-00249	Unveiling the structure of neutron-rich Z=9 isotopes: the case of 25F	Panin, Valerii		12
G-24-00302	Test of the DESPEC Implantation Stack Detectors	Albers, Helena	23	

Table 1: List of user experiments in 2025 and accounted beamtime in 8h shifts. Secondary beam users get on the average 10% of the available beam time.

2. Research of the APPA Departments

Coordination: Prof. Dr. Thomas Stöhlker (Helmholtz Institute Jena, Friedrich Schiller University Jena & GSI)

2.1 Executive summary

Author: Thomas Stöhlker

At GSI, the research departments Atomic Physics, Biophysics, Plasma Physics, and Materials Research are organised under the roof of APPA/MML, where MML is the Helmholtz program "From Matter to Materials and Life", and APPA, "Atomic, Plasma Physics and Application", is one of the four research pillars of FAIR. Since 2025, APPA has further been strengthened by the newly formed organisational unit of "Nuclear Astrophysics" which is embedded both in APPA as well as in NUSTAR. With the intense ion beams, GSI and the future FAIR accelerators provide outstanding and worldwide unique experimental conditions for extreme matter research in atomic and plasma physics and for application-oriented research in biophysics, medical physics and materials science. The associated research activities comprise interaction of matter with highest electromagnetic fields, properties of plasmas and of solid matter under extreme pressure, density, and temperature conditions, simulation of galactic cosmic radiation, research in nanoscience and charged particle radiotherapy. A broad variety of MML/APPA-dedicated facilities including experimental stations, storage rings, and ion traps, equipped with most sophisticated instrumentation will allow the MML/APPA community to tackle new challenges (MML/APPA research at GSI contributes to all three research topics of the program MML).

Figure 1 depicts an overview of experimental stations devoted to MML/APPA physics at GSI and the future FAIR facility whereby all the facilities on the campus of GSI (Figure 1 panel a) are in user operation (re-commissioning of HITRAP has started in 2022). Currently, the GSI-MML facilities serve more than 450 users from universities and research institutes in over 30 countries and are the basis of the international APPA collaboration for FAIR (more than 800 members from 30 countries). In addition, GSI-MML cooperates with the European Space Agency (ESA). During FAIR Phase 0, GSI offers 3 months/year of beam time. The national university partners are funded by the German Federal Ministry of Research, Technology and Space (BMFTR) ErUM framework program, including the research priority program APPA. GSI-MML scientists support users throughout the entire process, including preparation and execution of the beam time as well as data storage and analysis.

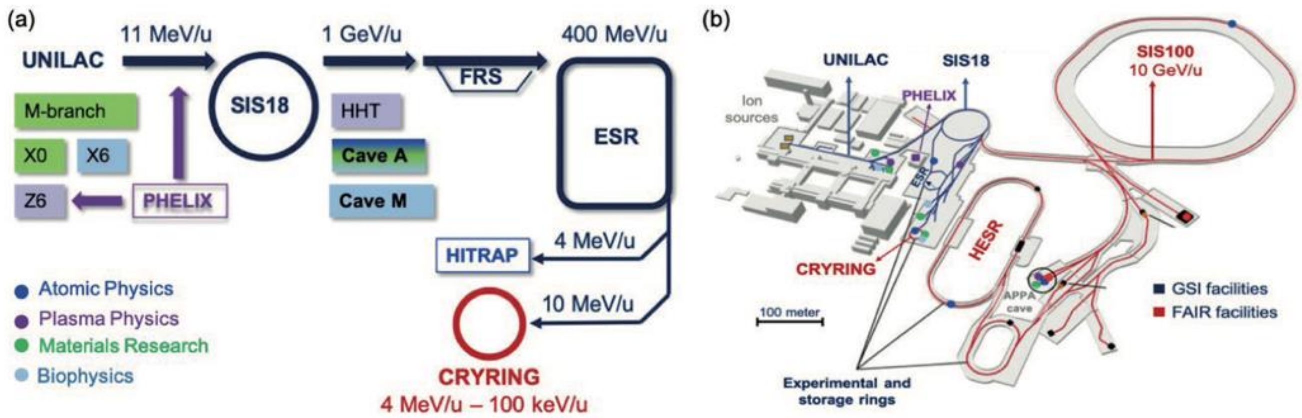

Figure 1: (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red) [1]

[1] T. Stöhlker *et al.*, "APPA at FAIR: From fundamental to applied research," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 365, pp. 680–685, 2015.

2.2 Atomic, Quantum, and Fundamental Physics

Head: Prof. Dr. Thomas Stöhlker (Helmholtz Institute Jena, Friedrich Schiller University Jena & GSI)

Authors: *Carsten Brandau (GSI), Alexandre Gumberidze (GSI), Nikos Petridis (GSI), Yuri Litvinov (GSI & Cologne University), Pierre-Michel Hillenbrand (GSI), Danyal Winters (GSI), Thomas Stöhlker (GSI, HI-Jena & Jena University)*

Below, we provide an overview of the research activities of the Atomic, Quantum and Fundamental Physics Research Department (AQF), which is embedded in FAIR's APPA pillar and in the MML (Matter) research program within the Helmholtz Research Field Matter. This overview also includes the activities of the Nuclear Astrophysics (FFP) organisational unit related related to APPA, which was founded in 2025 and is headed by Yuri Litivinov, professor at the University of Cologne. The FFP is embedded in both the MML research topic 'Matter' and the MU topic 'Cosmic Matter in the Laboratory,' thus forming a bridge between two research pillars of FAIR, namely APPA and NUSTAR.

In close cooperation with scientists from all over the world, and especially within the framework of the SPARC collaboration, part of the APPA research pillar at FAIR, the SPARC working groups of the department for Atomic, Quantum, and Fundamental Physics as well as the APPA part of Nuclear Astrophysics of GSI are concentrating their research efforts on precision experiments in the realm of atomic and fundamental physics. For this purpose, the storage ring / ion trap complex ESR / CRYRING@ESR / HITRAP (part of the modularised FAIR facility) offers fascinating, worldwide unique experiment possibilities by providing cooled heavy ion beams, for basically all elements (from hydrogen to uranium) in every charge state up to fully ionised uranium. A particular unmatched selling point of the storage ring/ion trap complex ESR / CRYRING@ESR / HITRAP is that cooled ions can be provided over a wide energy range from rest in the laboratory up to relativistic velocities of approx. 70% speed of light. The combination with the fragment separator (FRS) allows to extend the research spectrum to short-lived nuclides. All together, these unique and highly relevant research opportunities enable a rich spectrum of atomic physics experiments, with the main focus on the investigation of quantum dynamics and quantum electrodynamics in extremely strong Coulomb fields as they prevail in the heaviest highly charged ions (close to the Schwinger limit). In addition, atomic physics research at GSI extends to neighbouring fields such as accelerator physics, materials research, plasma physics, and especially atomic and nuclear astrophysics (see e.g., [1]). To reach its research goals, particular important activities of the AQF department are related to the development and implementation of novel, state of the art instrumentation (such as e.g., dense internal gaseous targets, lasers, X- and γ-ray polarimeters, cryogenic micro-calorimetric detectors for soft and hard X-rays, and non-destructive Schottky devices). Instrumentation and detection concepts are permanently under scrutiny and in case adjusted, to enable the most optimal use of the aforementioned research infrastructures.

In 2025, several beam times have been successfully carried out at the ESR and CRYRING@ESR facilities within the FAIR Phase-0 program. This also included the commissioning of new setups developed within the SPARC collaboration. In addition, a first official user experiment has taken place at HITRAP in March 2025 to study ion-surface interaction with heavy highly charged ions at low energies. This marks a very significant progress for HITRAP as a user facility.

Note, for many of the research activities presented below, the AQF department has teamed up with the Helmholtz Institute Jena, a research institute of GSI at the campus of the Friedrich-Schiller University of Jena, which in some cases even took the lead (cf. annual report of HI-Jena: https://www.hi-jena.de/en/publications/annual_reports).

Highlights in 2025

Using novel metallic magnetic calorimeter detectors at the CRYRING@ESR, we recorded x-ray spectra of stored and electron cooled heliumlike uranium (U^{90+}) with an unmatched spectral resolution of close to 90 eV [2] (see Figure 2). This allowed for an accurate determination of the energies of all four components of the Kα transitions in U^{90+}. We find good agreement with state-of-the-art bound-state QED calculations for the strong-field regime. Our results do not support any systematic deviation between experiment and theory in heliumlike systems, the presence of which was subject of intense debates in recent years.

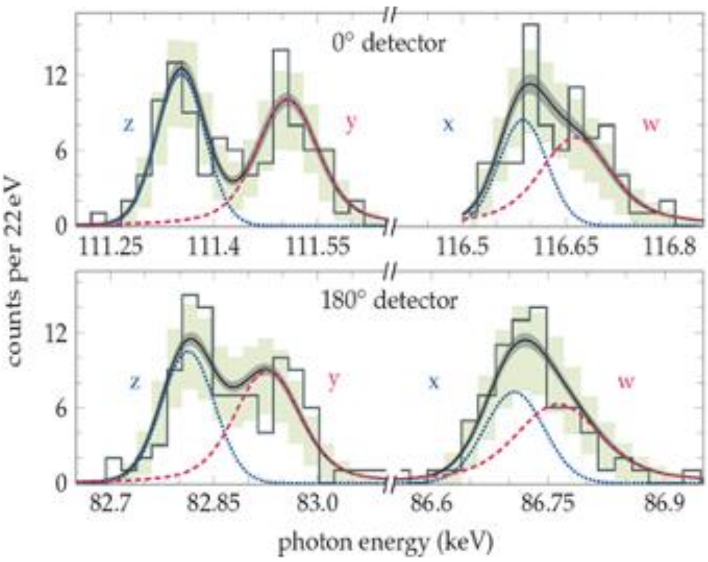

Figure 2: The measured spectra (histogram in grey) with the corresponding fit results. For the Kα regions the fit results are presented in detail: the model function (sum of Voigt profiles) is drawn as solid black lines. The grey bands surrounding them represent a one standard deviation wide confidence range resulting from the uncertainty of the optimised free parameters. The effects of counting statistics (Poisson distribution) are represented by the light green area. Finally for visual guidance the Voigt-shaped profiles of the individual components of the Kα transitions are shown as coloured dashed lines.

Testing Strong-Field QED to Second Order in the Highly Correlated Atomic System Berylliumlike Pb78+ by Electron-Ion Collision Spectroscopy

A low-energy storage ring with an ultracold electron cooler has been coupled with a heavy ion accelerator facilitating high-resolution electron-ion collision spectroscopy of the heaviest few-electron ions [3]. Namely, a resonant electron-ion recombination of berylliumlike Pb^{78+} ions was measured in the collision-energy range 9.3–16.5 eV and a value of 244.937(30) eV was derived for the $Pb^{78+}(2s^2\ ^1S_0–2s2p\ ^3P_1)$ excitation energy (see Figure 3). This result agrees with the most recent (less accurate) theoretical value of 244.942(52) eV [4], which has been calculated by applying strong-field QED rigorously up to the second order. The present investigation suggests that further technical improvements can potentially increase the experimental accuracy by an order of magnitude.

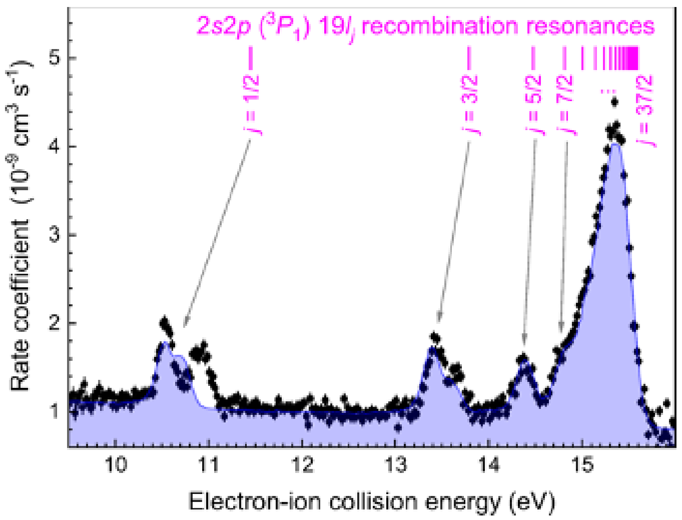

Figure 3: Comparison of the present experimental merged-beam rate coefficient for electron-ion recombination of Pb78+ (symbols with statistical error bars) with the results of our theoretical calculations with the auto-structure code (shaded full curve). The vertical bars denote the 2s2p(3P1)19lj DR resonance positions using again E_{exc}=244.937 eV and for $E_{b(nlj)}$ the Dirac formula for hydrogen-like ions with an effective nuclear charge of 78 for all 19 possible j values ranging from j=1/2 to j=19−1/2=37/2.

Storage-ring laser spectroscopy of accelerator-produced hydrogen-like $^{208}Bi^{82+}$

The very first measurement of the hyperfine-structure splitting in the 1s ground state of radioactive hydrogen-like $^{208}Bi^{82+}$ was performed at the ESR storage ring [4] (see Figure 4). The beam of the isotope of interest was produced in a nuclear reaction and was injected into the ESR to perform laser spectroscopy on samples of 10^5 ions of Bi^{82+} that have only a single remaining electron, which experiences extreme magnetic-field strengths. The result for the hyperfine splitting is in excellent agreement with the most accurate prediction based on a combination of quantum electrodynamics calculations with an empirical treatment of the hyperfine-structure anomaly ratio extracted from laser spectroscopy on neutral atoms of ^{209}Bi and ^{208}Bi. This achievement paves the way for the most stringent test of quantum electrodynamics in strong magnetic fields and demonstrates the feasibility of laser spectroscopy on other exotic ions with low production yields.

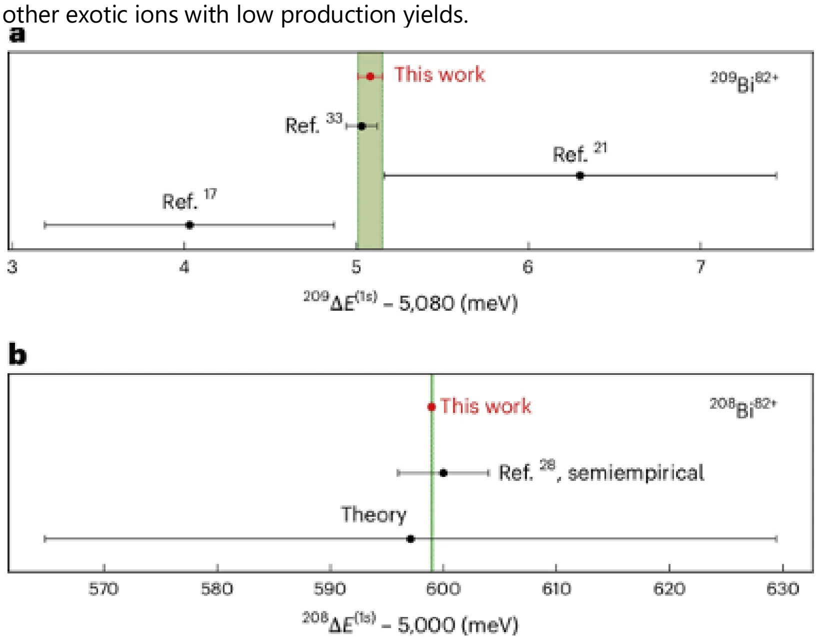

Figure 4: (a) Comparison of the ground-state HFS energy 209ΔE(1s) of H-like $^{209}Bi^{82+}$ obtained in this work with previous experiments. The excellent agreement in this initial test measurement assures the performance of the system and the detection scheme, and provides a 25% uncertainty reduction as compared with other work. (b) HFS energy $^{208}\Delta E^{(1s)}$ of the H-like radioisotope $^{208}Bi^{82+}$ measured in this work compared with the semiempirical prediction and a theoretical calculation analogue but using the independently measured magnetic moment. Our value shows an excellent agreement with both but is 50 times more precise than the best one, as indicated by the green uncertainty band. All uncertainties represent 1σ (k = 1).

First Proton-Induced Cross Sections on a Stored Rare Ion Beam: Measurement of 118Te(p,γ)for Explosive Nucleosynthesis

The first proton-induced reaction measurements on a stored radioactive ion beam have been successfully conducted, studying ^{118}Te(p,γ) and ^{118}Te(p,n) reactions at the ESR [5]. By the unique combination of the Fragment Separator (FRS) and the ESR, the production and storage of the radioactive isotope ^{118}Te was accomplished. At this point, about 10^6 ions of bare $^{118}Te^{52+}$ with a storage lifetime of about 1.5 s were collided with the H_2 target to trigger p-induced reactions. The reaction products were separated from the primary beam in the dipole magnet of the ESR and detected by a dedicated DSSD mounted on a movable actuator. This breakthrough opens access to key reactions in explosive nucleosynthesis for the γ-process. Absolute cross sections were measured at centre-of-mass energies of 6, 7, and 10 MeV, just above the astrophysical Gamow window (see Figure 5). Theoretical models have been constrained by the measurements, enabling reliable extrapolations to stellar conditions.

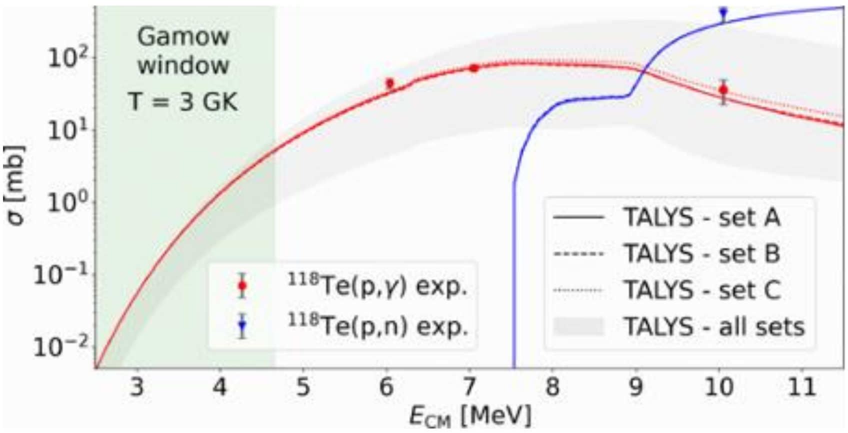

Figure 5: Cross sections of ^{118}Te(p,γ) in red and ^{118}Te(p,n) in blue are depicted for the measurement region and the Gamow window at T=3 GK. The experimental data is shown in overlay with TALYS calculations based on the three parameter sets that generate the best reproduction. The grey band represents the full parameter space available in TALYS without individual tuning of the underlying models.

3. First Measurement of the Neutron-Emission Probability with a Surrogate Reaction in Inverse Kinematics at a Heavy-Ion Storage Ring

Neutron-induced reactions of short-lived nuclei play a prominent role in the origin of heavy elements in stellar nucleosynthesis, but measurement of the corresponding cross sections is extremely complicated due to the radioactivity of the targets involved [6]. The first surrogate-reaction experiment in inverse kinematics at a heavy-ion storage ring has been achieved within the NECTAR project, measuring neutron-emission probability for ^{208}Pb in the ESR. Using the ^{208}Pb(p,p') as a surrogate for neutron capture on ^{207}Pb, the neutron-emission probability as a function of excitation energy was measured (see Figure 6). Thanks to the outstanding detection efficiencies possible at the ESR, the beamlike residues formed after neutron emission were detected with an efficiency of 100%, thus enabling us to measure for the first time the neutron-emission probability as a function of the excitation energy of ^{208}Pb. γ-ray strength functions and nuclear level densities have been constrained by these results, providing reliable predictions for ^{207}Pb(n,γ) cross sections at energies where no experimental data exist.

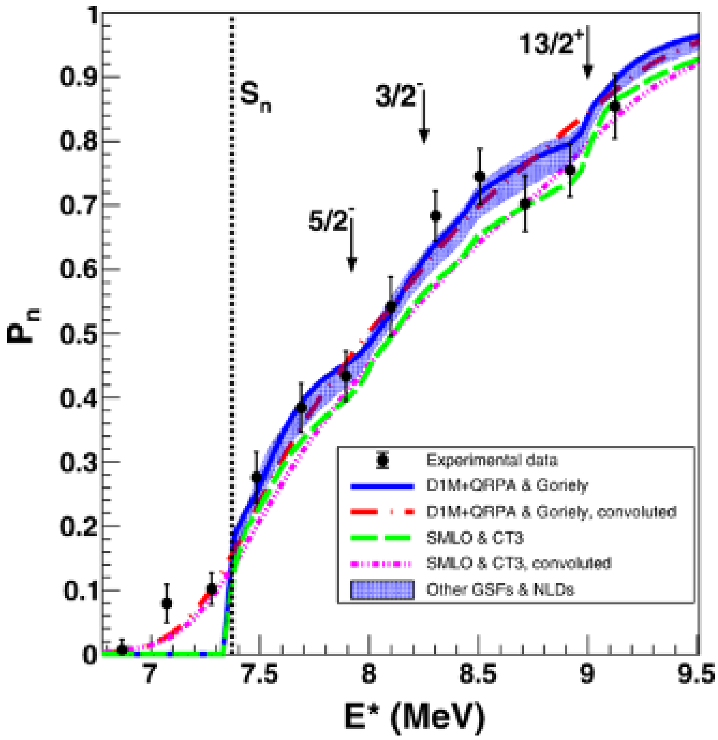

Figure 6: Neutron-emission probability as a function of the excitation energy E* of ^{208}Pb measured for the ^{208}Pb(p,p') reaction in comparison with TALYS calculations. The arrows indicate the E* at which the three first excited states of ^{207}Pb become accessible. The spin and parity of the states are also given. The neutron separation energy Sn of ^{208}Pb at E*=7.37 MeV is indicated by the vertical dotted line.

FAIR Phase-0: experiments

The Experimental Storage Ring

Laser spectroscopy of Li-like ^{208}Bi ions

In order to provide an independent test of bound-state strong-field QED that is decoupled from nuclear size effects, i.e., the Bohr–Weisskopf effect, the so-called specific difference must be measured for two isotopes that exhibit a large difference in their nuclear magnetic moment contributions. This approach was pursued for H-like and Li-like $^{208/209}$Bi ions in successive beamtimes at the ESR. During the experimental campaign in May 2025 the last remaining hyperfine splitting of $^{208}Bi^{80+}$ was successfully studied using laser spectroscopy of bunched Bi ions at energies of 374 MeV/u. Because of the low production rates of $^{208}Bi^{80+}$, a novel detection scheme was applied, based on charge exchange and subsequent particle detection, exploiting the selectivity of the resonant dielectronic recombination process into the excited hyperfine state.

CRYRING@ESR

Dielectronic Recombination of F^{6+} as a benchmark for the CRYRING@ESR electron cooler in internal target mode

Low-energy dielectronic recombination (DR) of lithium-like F^{6+} was investigated at the CRYRING@ESR providing a benchmark for tuning the electron cooler. The narrow ~10 meV DR resonance provided a sensitive probe of collision velocity spreads, allowing machine optimization for highest spectroscopic resolution and establishing settings applicable to future DR studies of other atomic systems.

Absolute rate coefficients from dielectronic recombination for the astrophysically relevant ion O^{2+}

Electron–ion collisions of O^{2+} were studied at the CRYRING@ESR through measuring energy-resolved dielectronic recombination (DR) rates from 0–45 eV and comparing them with AUTOSTRUCTURE calculations. The data covered $\Delta N=0$ and $\Delta N=1$ DR series, with evidence for metastable contributions in the ion beam. From these results, a temperature-dependent plasma DR rate coefficient was derived, thereby finding good agreement with theory at high-temperature plasma conditions but about twice larger rates in the photoionised regime.

SPARC transverse free-electron target

In March 2025 the SPARC transverse free-electron target presently installed in the experimental section YR09 of the CRYRING@ESR was successfully commissioned with a heavy ion beam injected via SIS/ESR. The BMFTR funded SPARC transverse electron target has been primarily developed in a collaboration of the Justus-Liebig-University Giessen and GSI and serves as a generic target station for atomic physics electron-ion collision studies. In the commissioning run, it could be shown for the first time that such a dense electron beam (> 10^8 e/cm^3) can be operated in storage ring in conjunction with a very heavy ion beam (Au^{75+}). The detailed technical investigations of mutual interactions of the electron and ion beams are complemented by first X-ray spectra observed at the new experimental set-up. With the completion of commissioning of the transverse electron target a further milestone of the SPARC collaboration towards FAIR has been reached.

Gas-jet target at CRYRING

In 2025, substantial progress has been achieved at the internal gas-jet target of the CRYRING@ESR. The optimizations undertaken included among others; a substantial increase of the pumping speed and a corresponding improvement of the vacuum in the nozzle chamber. In addition, the procedure for handling the nozzle has been significantly improved. These optimizations have made it possible to increase the available target densities in particular for H_2 and D_2 gases by up to a factor 1000. This was a crucial prerequisite for the successful measurements with the CARME setup (see next sub-section). Furthermore, a dedicated control system called DAEDALUS has been developed allowing manipulation and display of all the relevant target parameters in real time.

CARME detector array at CRYRING

In May and June 2025, the CRYRING facility was used to store beams from its local ion sources for the CARME Experiment in order to investigate low-energy nuclear fusion reactions of relevance for astrophysics (see Figure 7). One of the milestones reached in this period was the storage and cooling of an intense deuterium beam at 90 keV/u, representing the lowest beam energy stored in the CRYRING@ESR yet. By using a deuterium gas target, the D+D fusion reaction could be studied inside the Gamow window for the Big Bang Nucleosynthesis, shedding a new light on the D(D,p)T and D(D,n)^{3}He reactions that carry the dominant uncertainties in this scenario.

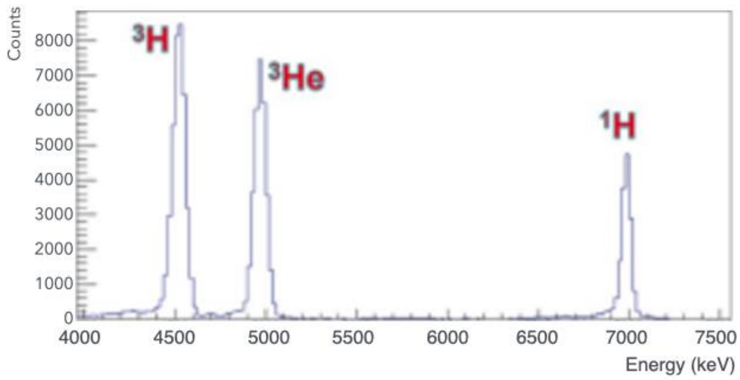

Figure 7: The energy spectrum of the CARME Si detectors showing three distinct peaks for reaction products of D+D nuclear fusion.

HITRAP

Ion-surface interaction experiments with heavy HCI at HITRAP

For HITRAP, the central ion trapping facility for SPARC, substantial progress has been achieved by the decelerator department to slow down Au^{79+} ions and to store them in the cooler trap. Moreover, a first official user experiment has taken place at HITRAP in March 2025 to study ion-surface interaction with heavy highly charged ions at low energies. Cooled bunches of bare gold ions $^{197}Au^{79+}$ were extracted from the ESR storage ring at an energy of 4 MeV/u towards HITRAP, decelerated in the IH and RFQ structures to 6 keV/u, and guided onto bulk samples, such as CaF_2, Monolayer Graphene (on SiC substrate), and MoS_2 (on Au/SiO_2). Upon impact on a surface, slow heavy highly charged ions deposit large amounts of their potential energy within the very first monolayers of the material. Depending on material properties, relaxation processes can lead to permanent nano-sized material modifications, such as formation of hillocks and craters on the surfaces of the bulk samples. The modifications are analysed offline with methods as atomic force microscopy. This is uncharted territory since ion-surface studies have never been performed before with a potential energy larger than 0.5 MeV as in $^{197}Au^{79+}$, in the regime where the potential and kinetic energies are comparable.

Laser cooling at SIS100

In 2025 several milestones could be reached. First of all, two vacuum chambers for laser cooling at the SIS100 were transported to and installed in the accelerator tunnel. Figure 8a) shows the vacuum chamber (ILBI) where the laser light will be coupled into the accelerator. Figure 8b) shows the vacuum chamber (EFAO), provided by Münster University, which is a fluorescence spectrometer for laser cooling and laser spectroscopy. We could also purchase the XUV master grating. Figure 8c) shows the installation of „part 2" of the laser beamline in the accelerator tunnel. In January 2021, "part 1" was installed during the civil construction of the SIS100 tunnel itself. (It cannot be seen in the photo.) The laser beamline will be extended vertically downwards, when other installations in the tunnel are completed. Finally, see Figure 8d), the construction of the laser lab in the SIS100 maintenance tunnel was started. The lab has an area of 50 m^2 and will contain two optical tables for in total 3 different laser systems (1x cw laser system and 2x pulsed laser systems). From this lab, the laser beams go through the beamlines part 1 and part 2 to the SIS100 accelerator. Also worth mentioning are the new simulations that were done for laser cooling. These were taking into account realistic laser powers, intrabeam scattering and space charge effects. Also, the effects of bunching of the ion beam were studied more carefully. These simulations confirmed that the relative longitudinal momentum spread of the ion beam can be reduced from an initial $\Delta p/p=10^{-3}$ down to 10^{-8} within a few 10 seconds, using all three laser beams.

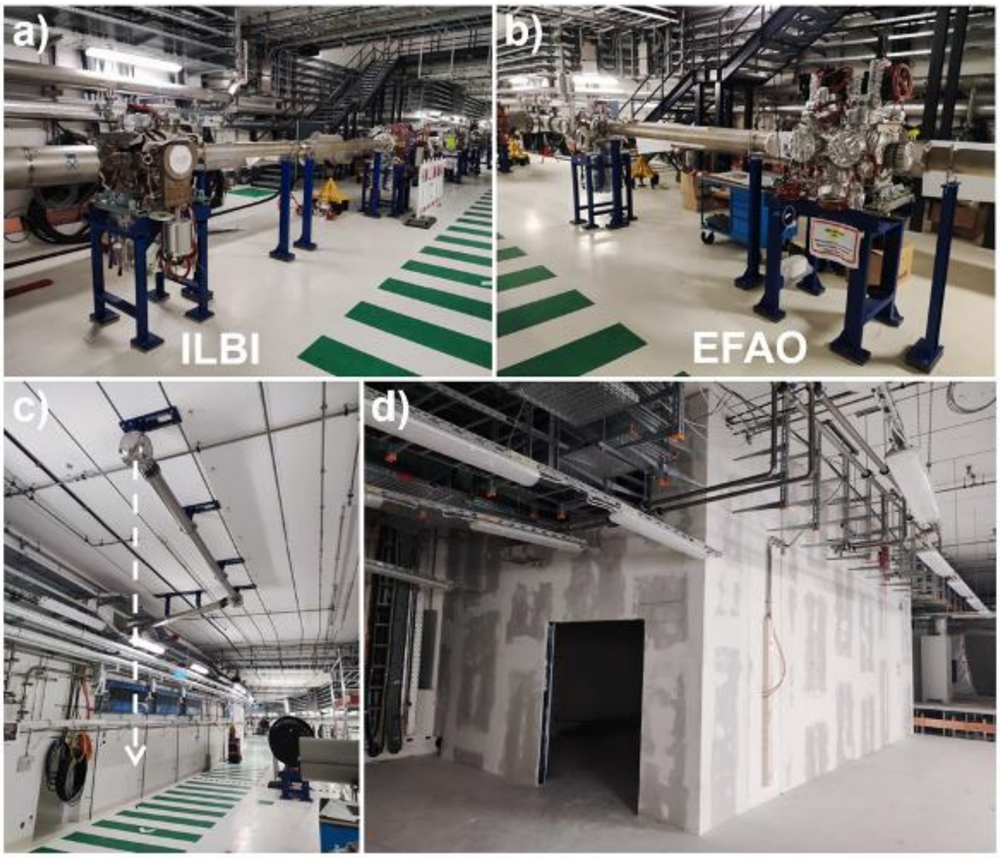

Figure 8: (a) the vacuum chamber (ILBI) where the laser light will be coupled into the accelerator. (b) the vacuum chamber (EFAO), which is a fluorescence spectrometer for laser cooling and laser spectroscopy. (c) installation of „part 2" of the laser beamline in the accelerator tunnel. (d) the laser lab in the SIS100 maintenance tunnel.

Selected publications of 2025

[1] L. Varga et al., "Nuclear astrophysics in the storage ring: Background suppressed simultaneous measurement of (p, γ) and (p, n) reactions," Phys. Rev. Lett., vol. 134, p. 082701, Feb. 2025, doi: 10.1103/PhysRevLett.134.082701.

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[5] M. Horst et al., "Storage-ring laser spectroscopy of accelerator-produced hydrogen-like $^{208}\mathrm{Bi}^{82+}$," Nature Physics, vol. 21, no. 7, pp. 1057–1063, July 2025, doi: 10.1038/s41567-025-02885-x.

[6] S. F. Dellmann et al., "First proton-induced cross sections on a stored rare ion beam: Measurement of $^{118}\mathrm{Te}(\mathrm{p}, \gamma)$ for explosive nucleosynthesis," Phys. Rev. Lett., vol. 134, p. 142701, Apr. 2025, doi: 10.1103/PhysRevLett.134.142701.

[7] M. Sguazzin et al., "First measurement of the neutron-emission probability with a surrogate reaction in inverse kinematics at a heavy-ion storage ring," Phys. Rev. Lett., vol. 134, p. 072501, Feb. 2025, doi: 10.1103/PhysRevLett.134.072501.

2.3 Materials research

Head: Prof. Dr. María Eugenia Toimil-Molares (GSI & Technical University Darmstadt)

Introduction

Authors: *Gregorio Laucirica (GSI), Christopher Schröck (GSI & Goethe University Frankfurt), Marilena Tomut (GSI & University of Münster), Maria Eugenia Toimil-Molares (GSI & TU Darmstadt)*

The activities of the Materials Research Department encompass a broad range of projects focused on ion-track nanotechnology and the interaction of swift heavy ions and solid-state matter. Key areas of research include

· ***Ion-track-etched nanochannels and nanowires***: Tailored membranes with single- or multi-channels are developed for sensor applications. Additionally, size-dependent properties of electrodeposited three-dimensional nanowire networks are systematically investigated. The overarching aim is to develop metal nanowire networks for catalytic, thermoelectric and energy-related applications.

· ***Heavy-ion-induced material modification***: Radiation damage is studied in a wide range of bulk and nanostructured materials, including ceramics, high-entropy alloys, functional materials, space ices analogs, thin films, and nanowires.

· ***Materials under multiple extreme conditions***: The response of materials to combined extreme conditions is of fundamental importance for both the synthesis of novel materials and for geoscientific studies simulating processes in the Earth's mantle. High pressure, high temperature, and high radiation doses - applied individually or in combination - induce significant changes in the atomic and electronic structure of materials. Heavy-ion beams delivered by the SIS18 accelerator (and, in the future, SIS100) can penetrate several mm into diamond anvil cell (DAC). The high energy deposition in the pressurised sample drives the system far from equilibrium. The combination of ion irradiation and high static pressure enables the formation and stabilization of unique structural changes that cannot be achieved by ions or high pressure alone.

To support the interdisciplinary MAT collaboration, comprising more than 40 research groups from Germany and abroad, the Materials Research Department maintains and operates several beamlines equipped with a wide range of in-situ analysis techniques: X0 and M-branch (at UNILAC), Cave A (at SIS-18) and the newly established Mat-Station at CRYRING.

Highlights in 2025

Formation of single-phase crystalline and amorphous high-entropy ZrTiTaMoWNi thin films under near-equilibrium condensation conditions

High-entropy alloys (HEAs) consist of multiple principal elements and exhibit unique structural and functional properties, with phase formation strongly dependent on composition and processing conditions. Typically comprising five or more elements (5–35 at.%), their high configurational entropy stabilizes single-phase solid solutions by lowering Gibbs free energy. HEAs are known for their exceptional properties, including high strength, thermal stability, and resistance to corrosion and oxidation, making them promising candidates for demanding applications such as radiation-resistant coatings in nuclear systems.

Phase formation is influenced by factors such as atomic size mismatch, electronegativity, and valence electron concentration: small atomic size differences favor solid solution formation, whereas larger mismatches promote amorphous structures. Magnetron sputtering is widely used for the fabrication of HEA thin films due to its precise control over composition and microstructure, enabling the formation of crystalline, amorphous, or nanostructured phases. However, achieving controlled crystalline phase formation remains challenging, as the amorphous-to-crystalline transition depends on thermodynamic conditions in the plasma–condensate system, particularly near equilibrium.

In a newly published study [1], Zr–Ti–Ta–Mo–W–Ni thin films were synthesised by magnetron sputtering to investigate the influence of sputtering power, substrate temperature, and Ni concentration. Amorphous, chemically homogeneous coatings form at Ni concentrations of 8–15 at.% under low supersaturation conditions and crystallize into a single body-centred cubic (bcc) phase upon annealing at 800 °C. At lower Ni content (~3 at.%), bcc nanocrystals nucleate with preferential orientation.

The radiation resistance of the thin films was evaluated by irradiation with 4.8 MeV/u Au ions at the UNILAC accelerator at GSI. The amorphous films exhibit enhanced resistance to high-energy ion irradiation, highlighting their potential as radiation-resistant protective coatings (see Figure 9).

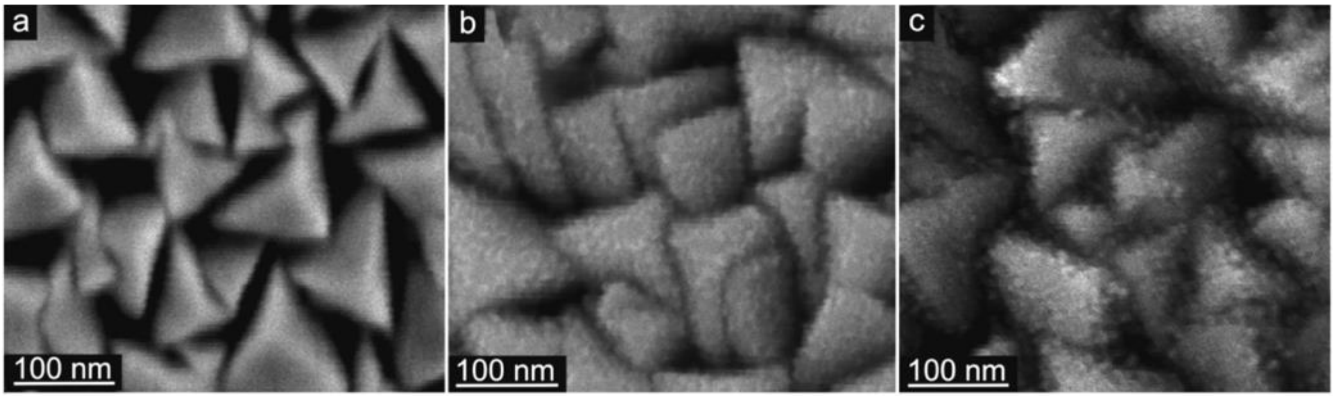

Figure 9: SEM investigations of the surface morphology of a nano-columnar ZrTiTaMoWNi crystalline thin film irradiated with 4.8 MeV/u Au ions: (a) pristine (a), and exposed to a fluence of (b) $5x10^{12}$ Au ions/cm^2 and (c) $5x10^{13}$ Au ions/cm^2 respectively. From Ref. [1].

Influence of diameter on high-pressure induced phase transitions in bismuth nanowire networks

Nanomaterials exhibit physical and chemical properties that differ significantly from their bulk counterparts. Therefore, investigating the impact of systematically adjusted dimensions on the material properties is crucial for optimizing performance through geometry control. In another recently published work, the size-dependent behaviour of bismuth nanowire networks under high-pressure conditions was investigated at room temperature.

Three-dimensional networks of freestanding interconnected bismuth nanowires with diameters between 34 and 85 nm were synthesised by electrodeposition in ion-track etched membranes, alongside microcrystals serving as bulk analogues. The templates were prepared from polycarbonate foils irradiated at the X0 beamline of GSI Helmholtz Centre Darmstadt, Germany. Both types of samples were simultaneously compressed in diamond anvil cells under hydrostatic conditions up to 19.5 GPa.

Synchrotron x-ray diffraction data reveal a systematic shift of the Bi-I/-II, Bi-II/-III, and Bi-III/-V phase transitions to higher pressure values with decreasing nanowire diameter. For the thinnest nanowires, compression and decompression cycles revealed hysteresis-like behaviour, accompanied by a pronounced coexistence of the Bi-III and Bi-V phases during compression.

All samples display bulk-like compression behaviour, as reflected in the evolution of their lattice parameter and bulk modulus. Only nanowires in the Bi-III phase showed a slightly reduced modulus compared to the corresponding bulk value (see Figure 10).

The observed systematic size dependence underscores the importance of precise geometrical control and consistent experimental conditions. The mechanical stability of the three-dimensional nanowire networks prepared by ion-track nanotechnology and electrodeposition, enables pressurization of samples with varying wire diameters under identical experimental conditions, providing a robust platform for systematic studies of size effects in nanomaterials down to diameters of ~10 nm. [2]

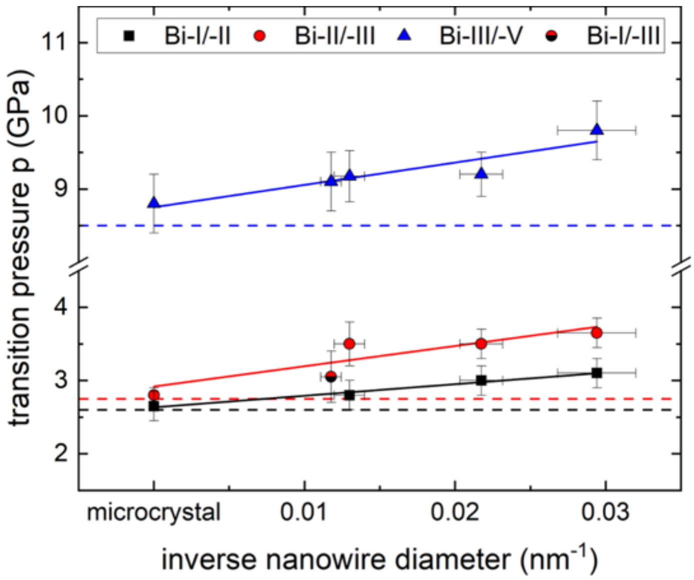

Figure 10: Transition pressures of Bi-NWNWs and microcrystals [2]. Horizontal lines correspond to bulk transition values reported in the literature [3].

Expanding the synergy between MOFs and solid-state nanochannels: robust anchoring of enzymes for iontronic biosensing

The integration of biological recognition elements into solid-state nanochannels enables the development of highly selective sensing strategies, in which surface charge modulation governs ion transport. However, conventional approaches based on polymeric coatings or electrostatic assembly often suffer from limited chemical and mechanical stability.

In a recent collaborative work between Universidad de La Plata and GSI, we demonstrate a nanofluidic biosensor based on track-etched polyethylene terephthalate (PET) nanochannels functionalised with the zirconium-based metal-organic framework (MOF) UiO-66-NH_2. The track-etched PET membranes were prepared by irradiation of PET foils with swift heavy ions at the UNILAC linear accelerator (GSI, Darmstadt), followed by alkaline chemical etching. Subsequently, UiO-66-NH_2 was grown directly within the confined geometry of the bullet-shaped nanochannels. The urease enzyme was then covalently immobilised on the amino groups from MOF by using divinyl sulfone.

The resulting nanochannels exhibit pronounced pH-dependent ionic transport, arising from the coupled protonation and deprotonation equilibria of both the MOF and the immobilised enzyme. This pH-responsiveness is exploited for urea sensing, as enzymatic hydrolysis of urea generates ammonia, leading to localised pH changes within the nanochannels. The changes are effectively transduced into modulations of ionic current and rectification behaviour (see Figure 11).

The biosensor achieves a detection limit of 10 µM for urea, while demonstrating excellent reversibility, high stability under elevated ionic strength and extended voltage ranges, and high specificity against interfering species. To our knowledge, this work represents the first nanofluidic sensor combining MOF-functionalised nanochannels with a covalently anchored enzyme, highlighting the potential of post-synthetica MOF modification for robust and advanced nanofluidic biosensing applications.

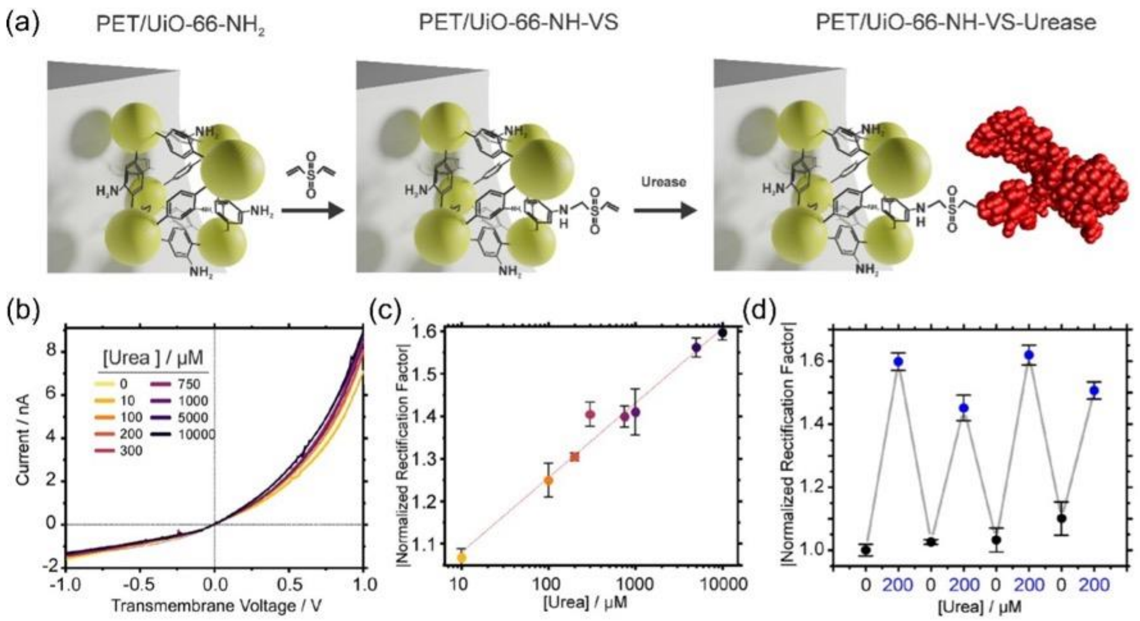

Figure 11: (a) Scheme of enzyme anchoring on UiO-66-NH_2 surface via DVS crosslinking. (b) I–V curves of the modified membranes measured in 100 mM KCl (pH 6.00) at different urea concentrations. (c) Semi-logarithmic plot of signal as a function of urea concentration. (d) Reversibility test during cyclic exposure to 200 µM urea solution.

Outlook 2026

In 2026, the department will further strengthen its role in cutting-edge materials research through continued involvement in the cross-centre Helmholtz Innovation Pool project MATHIPE (Materials under High Pressure) and the BMFTR Fusion collaborative project DINERWA. Building on these efforts, a major new third-party funded initiative, SIBAF, will commence in 2026. Within SIBAF, the department will lead the design and construction of an advanced irradiation chamber for fusion materials. This facility will be integrated with the prototype of Cryomodule 1 of the future HELIAC accelerator, which will be upgraded to continuous-wave (cw) operation in collaboration with the accelerator division—marking a significant milestone in accelerator-driven fusion materials testing.

In parallel, the department will broaden its nanotechnology activities through the launch of two innovative collaborative projects. MultiDRUG, funded by the Hessen LOEWE program, seeks to enhance personalised care for paediatric cancer patients by developing a highly selective biosensing platform based on biophotonics. This project is coordinated by TU Darmstadt, with partners from GSI and Goethe University Frankfurt. Complementing this, the Cluster4Future initiative Nanodiag BW utilizes nanopore-based biosensing technologies to analyse individual molecules and investigate disease-relevant epigenetic factors associated in conditions such as cancer, Alzheimer's, and diabetes. The network brings together universities, research institutions, and industry partners to accelerate the translation of novel research into diagnostic applications.

These initiatives collectively strengthen the department's interdisciplinary profile, reinforcing its contribution to advancing research at the intersection of materials science, functional material development, and nanotechnology applications.

Selected publications

[1] A. Kornyushchenko, V. Perekrestov, M. Tomut, H. Rösner, M. Peterlechner, and G. Wilde, "Formation of single-phase crystalline and amorphous high-entropy ZrTiTaMoWNi thin films under near-equilibrium condensation conditions," Journal of Alloys and Compounds, vol. 1047, p. 184918, 2025, doi: 10.1016/j.jallcom.2025.184918.

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2.4 Plasma physics

Head: Prof. Dr. V. Bagnoud (GSI, Helmholtz Institute Jena & Technical University Darmstadt)

Introduction

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High energy density (HED) plasmas, with pressures in the range of millions of atmospheres (Mbar), are relevant for our understanding of astrophysical objects such as planets and stars, the interaction of (ultra-) intense laser pulses with matter, and for achieving thermonuclear fusion by inertial confinement. Using powerful drivers such as large laser facilities and accelerators such extreme states of matter can be created and studied in the laboratory.
The Plasma Physics Department operates several experimental facilities at GSI for experiments in the field of HED science. At the target area Z6 in the experimental hall of UNILAC, a unique combination of ion pulses from the linear accelerator and laser pulses from the high-energy laser PHELIX allows for precise measurements of the ion stopping power in laser-generated hot plasmas, as well as to investigate advantages of combining laser accelerated ions with conventional accelerator technology. Stand-alone laser experiments can be performed in the PHELIX laser hall, where relativistic intensities in high-energy picosecond pulses are available for experiments on relativistic laser-matter interaction, laser-particle acceleration and the generation of intense secondary sources. Finally, at the high-temperature experimental station HHT at the output of the SIS18 synchrotron, heavy ion pulses with $>10^9$ ions per bunch can be focused to millimetre spot sizes and compressed to sub-μs duration, allowing macroscopic samples to be volumetrically heated to extreme conditions [1]. With the recently completed high-energy laser beamline from the PHELIX building to the HHT cave, experiments combining this novel way to create extreme states of matter with diagnostic techniques based on laser-driven secondary sources can be carried out.
Within the current FAIR Phase-0, these GSI facilities are also essential for the research program of the international FAIR collaboration HED@FAIR, which aims at exploiting the unique ion beam parameters that will be available in the APPA cave for HED science experiments. The plasma physics department as the GSI-based part of HED@FAIR coordinates the on-site activities preparing the technical and experimental infrastructure and diagnostic setups.

Operation report of the plasma physics user facility

During the reporting period, eight experiments were conducted at PHELIX. Three of these were done at the PHELIX target area (PTA), three at HHT, and two at Z6. Very unusually, two beamtimes had to be cancelled, including a three-week experiment applied for by collaborators from the USA, for which funding was not secured on short notice. This led to an unusual distribution of usage, with only 10% spent on experiment preparation and 24% on beamtime. On a long-term average, experiment preparation and beam time account for about half of usage, about 10% for internal experiments, and maintenance accounting for only one-third.

In 2025, maintenance and upgrades, as can be seen in Figure 12, were significantly overrepresented, accounting for more than half of the available time. The time was used for necessary major upgrades, e.g., the installation of a sixth amplifier head in the main amplifier section of PHELIX in order to increase the energy reserve of the overall system. In addition, two new large compression gratings arrived at GSI in 2025, the procurement of which had taken a long time and which serve as replacements for the already damaged gratings in the PTA.

Of the 373 experimental shots fired at the target in 2025, only about 3% are listed as failed shots in the PHELIX shot data base, demonstrating the high reliability of the facility, a consequence of the strong emphasis on maintenance and quality control of the system.

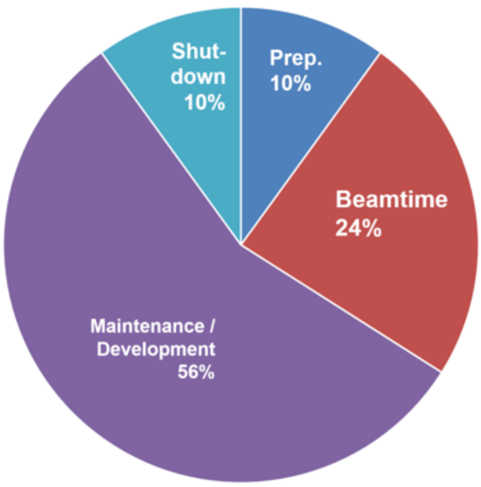

Figure 12: Statistics of PHELIX operation in 2025.

Highlights in 2025

Within the LIGHT project (Laser Ion Generation Handling and Transport) we work towards advancing methodologies for measuring energy loss in plasma. In the course of the 2025 beam time, a novel experiment was conducted in which carbon ions accelerated by the PHELIX laser were combined with a plasma generated by the nhelix laser. In this experiment, carbon ions were accelerated by the TNSA mechanism in the Z6 target chamber, and 0.5 MeV/u carbon ions were collimated by a pulsed solenoid, and transported by the LIGHT ion beam line over a distance of several meters to a second target chamber. A buncher cavity, driven by the UNILAC HF, compressed the ion pulse to a length of 1 ns at the plasma target position, and a second pulsed solenoid focused the ions onto the plasma target in the Z4 target chamber. The plasma target was created by irradiating a carbon foil from both sides with two laser beams (each with a pulse energy of 30 J at a wavelength of 527 nm) from the nhelix laser, focused to a spot size of 1mm diameter. Subsequent to the passage of the ions through the plasma target, the divergent ion beam was recollimated by a third solenoid and directed onto a diamond detector. This detector was specifically engineered for the detection of low-energy ions, utilizing a comb structure as electrodes to enhance the detection of ions stopped close to the surface. Preliminary tests had shown a significant improvement in sensitivity for detecting low-energy ions, compared to previously employed sandwich diamond detectors. While the data from the stopping power experiment is still being analysed, preliminary findings indicate that the energy loss is even lower than measured in earlier experiments, suggesting that existing theories may overestimate the energy loss in plasmas.

At PHELIX, we have performed a first experiment on electron acceleration in the self-modulated laser wakefield acceleration regime. With laser pulses of 500 fs and 100 J of laser energy (peak power 200 TW), we have produced electron beam charges of (500 ± 160) nC, results comparable to those obtained at much larger laser facilities such as OMEGA EP (US) and LMJ-Petal (France). With the full laser power of PHELIX and optimization of the acceleration scheme, this could be enhanced to the µC-level. Such high-charge electron bunches can be used to generate high-brightness x-ray and gamma ray beams, applicable for diagnostic purposes in High-Energy-Density physics experiments relevant for the IFE regime. Even for low laser pulse energies down to 10's of Joule, 100 nC charges could be achieved (see Figure 13). This will offer promising means for the application to high-average power picosecond laser systems, in the 10 to 100 Hz range, generating 10's of µA of average electron beam current, comparable to conventional linear electron accelerators used for the generation of radioisotopes.

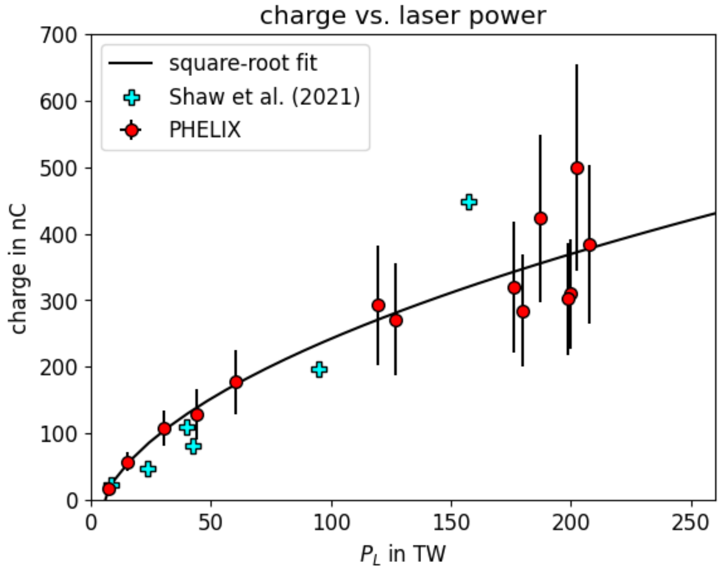

Figure 13: Resulting bunch charges from an experiment at PHELIX accelerating electrons by self-modulated laser wakefield acceleration.

High-current relativistic electron beams have also been generated via the direct laser acceleration (DLA) mechanism. Focusing 200 TW pulses from the PHELIX laser into a near-critical plasma, produced by pre-ionizing low-density polymer foam targets, the directed fraction of DLA electrons with energies exceeding 7.5 MeV was determined to carry a charge of 20 to 30 nC. Using a high-Z converter, ultrabright, well-collimated MeV bremsstrahlung radiation was generated with up to 10^{11} photons per shot with energies exceeding 7.5 MeV. The neutron flux produced in photo-nuclear reactions reached $2\times10^{20}cm^{-2}s^{-1}$. DLA electrons were also used for the ultra-intense irradiation of various biological samples. The combination of 20–50 Gy of ionizing radiation delivered by the relativistic electron beam in a single laser shot and the world's highest dose rate of 70 Gy/ps makes this source unique for studying the FLASH effect.

At the HHT experimental area, experiments can use the unique combination of intense ion pulses from the SIS18 synchrotron with high-energy laser pulses from the PHELIX laser. In a beamtime in 2025, we have characterised for the first time heating and melting of monocrystalline iron upon intense irradiation with pulses of up to 3×10^9 uranium ions, using diffraction of laser-generated x-ray line emission as diagnostic. Furthermore, we have shown the potential of such powerful laser-generated x-ray sources to enable x-ray radiographic imaging, which is planned as diagnostic to monitor the hydrodynamic evolution of heavy-ion irradiated samples at FAIR.

With up to 200 J of laser energy in nanosecond pulses, the HHT area is also used for laser-only experiments. Recent installation of a specifically designed large-aperture non-linear crystal in the laser beamline to HHT now enables frequency doubling of high-energy laser pulses with a broad spectral bandwidth. In a first experiment using this new capability, pulses with a bandwidth of 0.5% at energies reaching 80 J were used to study the effect of spectral bandwidth on the growth of laser-plasma instabilities (LPI) [2]. Such studies are of importance for advancing laser-driven fusion schemes, in which LPI can strongly limit the implosion performance and achievable fusion gain. The experiment could indeed show that using broadband laser radiation, both stimulated Brillouin scattering (SBS) and Two-Plasmon Decay (TPD) can be significantly suppressed. At the same time however, stimulated Raman scattering was found to increase with bandwidth, concomitantly with an increased generation of hot-electrons. Our results thus highlight the need for more careful examination of the effects of bandwidth.

The PRIOR-II proton microscope at the HHT experimental area of the plasma physics department (see Figure 14) is currently undergoing a transition phase to enable rapid, high explosive-driven shock wave experiments in macroscopic samples of dense matter. Using the 4H4 fast extraction scheme from the SIS-18 synchrotrons, the propagation of shock waves in those samples as well as the corresponding density changes can be observed and measured with an inter-framing time of below 200ns, allowing for the determination of the dynamic equation of state of inhomogeneous, porous and brittle matter. Several international working groups are scheduled to conduct experiments on equation of state measurements of porous materials for asteroid defence purposes, development of new functional materials for reactor technology and space travel, and the exploration of new methods for material synthesis under extremely high, dynamic pressures. The unique spatial resolution of PRIOR-II, combined with the long range of high-energy protons in dense matter, will enable new insights that cannot be achieved with other imaging techniques such as X-rays.

The assembly, commissioning, and regulatory certification of the shock wave facility were successfully completed in 2025. This includes the blast test of a new confinement chamber rated for physics experiments with explosives up to 250 g TNT equivalent that will enable to reach pressures up to 1 Mbar and beyond in shocked samples. With the completion of the core facility, resources are now focusing on optimizing the shock wave generators used in order to prepare for the first planned experiments. For this, a partnership with the Fraunhofer Institute for Chemical Technology has been formed to develop, characterize and build custom small explosive devices to drive the upcoming physics experiments.

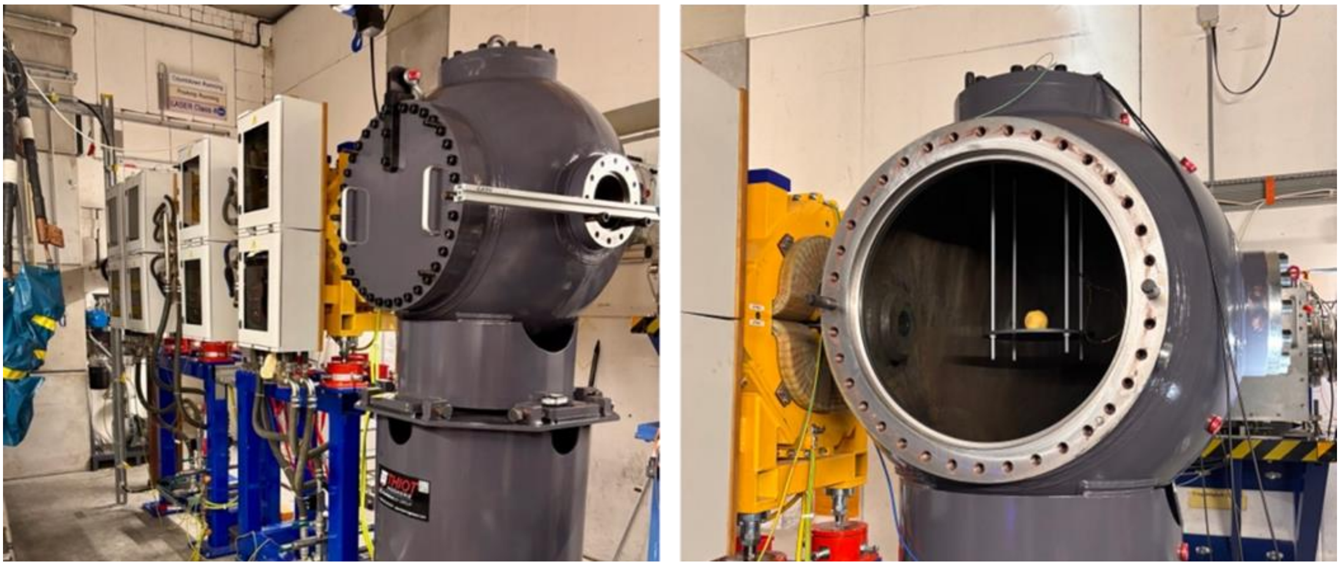

Figure 14: (left) The new confinement chamber mounted upstream of the PRIOR-II proton microscope in the HHT experimental area. (right) Initial blast test of the confinement chamber with about 190 g of plastic explosives.

Outlook 2026

As a consequence of the fire incident at GSI in early 2026, which severely damaged the HF-gallery of the UNILAC, experiments using ions from the GSI accelerator complex are currently not possible. Several granted beamtimes using the PHELIX laser in combination with ion beams, that were scheduled for 2026 had to be cancelled. Therefore, a proposal call for laser-only experiments with PHELIX was recently published, covering an experiment period until the end of 2027. It will depend on the selected short-term replacements and the duration of the repair works at the UNILAC, if combined experiments can again be applied for in 2028.

Being the most energetic pulsed laser facility in Germany, with particular expertise in large-aperture glass amplifiers and frequency doubling, PHELIX is well-positioned to play a strong role in the German efforts towards realizing laser-fusion. Given the political push within the German Hightech Agenda to develop fusion energy as a high-priority key technology, we have drafted several upgrade scenarios for PHELIX and for a future GSI-based laser facility. The goal is to offer to the scientific community a state-of-the-art large laser facility to tackle key issues in laser-based inertial fusion.

Selected publications of 2025

[1] P. Hesselbach et al., “Platform for laser-driven x-ray diagnostics of heavy-ion heated extreme states of matter,” Matter and Radiation at Extremes, vol. 10, no. 1, p. 017803, Dec. 2024, doi: 10.1063/5.0233548.

[2] C. Kanstein et al., “Experimental study of laser plasma instabilities with broadband laser pulses at the GSI PHELIX laser facility,” Plasma Physics and Controlled Fusion, vol. 67, no. 11, p. 115027, Nov. 2025, doi: 10.1088/1361-6587/ae1871.

2.5 Biophysics

Head: Prof. Marco Durante (Technical University Darmstadt & GSI)

Introduction

Authors: Prof. Dr. Marco Durante

The Biophysics Department studies the biological and medical applications of high-energy heavy ions, with two main applications: cancer therapy and space radiation protection. It is a highly interdisciplinary department, with currently 89 members with background in physics, biology, chemistry, and engineering. The Department is organised in 9 groups, 4 about physics and 5 about biology of heavy ions. The Department is characterised by high diversity, with 52% women and 42% foreign nationals from 16 different nationalities. The Department has pioneered heavy ion cancer therapy in Europe and is currently focusing on research in biological effects of heavy ions. The activity is largely supported by third-party funding, including ESA for space radiation research and ERC grants for cancer research.

International Biophysics Collaboration at FAIR

The Biophysics Department is part of the APPA pillar at FAIR. The International Biophysics Collaboration is a large network of accelerator facilities in operation or under construction with scientific programs in biomedical applications. The delay in the construction of the APPA cave (postponed to 2030) has been discussed within the collaboration and together with the Material Research Collaboration (BIOMAT). We decided to build simple setups to exploit the FAIR (SIS100) beam already from day-1, both at the S-FRS station (ring branch) and at the CBM cave. While at Super-FRS we will perform experiments with radioactive ion beams, in the CBM cave we plan to install the galactic cosmic ray simulator (GCRsim) commissioned in 2025 in Cave A with a cut-off at 1 GeV/u. In the CBM cave, we will reach the record energy of 10 GeV/u, making the FAIR GCRsim the most accurate experimental simulator of the cosmic ray spectrum worldwide. This is shown in Figure 15, where we present the LET and energy spectrum of the GCRsim measured during the last beamtime in 2025. While the LET spectrum is very close to the target spectrum (cosmic rays in deep space, 1 AU), the energy spectrum is obviously unsatisfactory. The large component 1-10 GeV/u can only be covered at FAIR. The initiative was approved by the FAIR Joint Scientific Council and the TDR for the setups have been approved by ECE/ECSG and RRB in 2025. We signed MoUs with both CBM and NuSTAR collaborations for the installations of Biophysics setup in the new caves. With this MoU, a given amount of time is allocated to IBC both at the ring branch and the CBM cave.

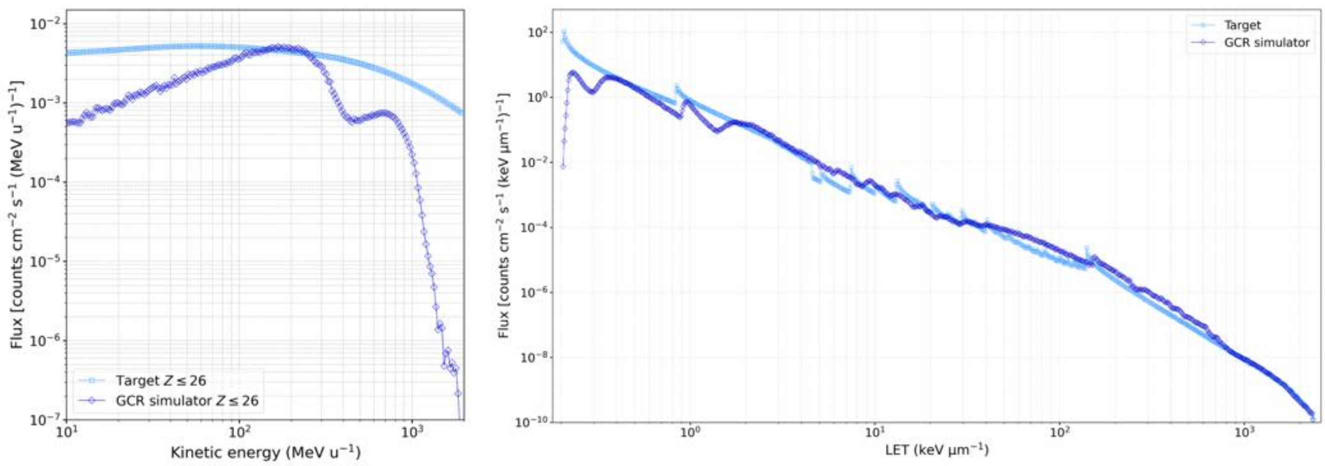

Figure 15: Output of the GSI GCRsim in Cave A. Left: energy spectrum. Right: LET spectrum. Measured spectra are compared with the "target" spectra of the real cosmic rays in deep space at 1 AU. This spectrum was used for the optimization of the range modulators used in the GCRsim at GSI, which use a single Fe-ion beam at different energies. The results show an excellent agreement with the planned LET spectrum, while the energy spectrum is poor because the energy is not high enough. We expect a much better agreement when the GCRsim will be moved to the CBM cave in FS+. Figures are from the ESA report on the GCRsim prepared by M. Durante, C. Schuy, E. Pierobon and L. Lunati, GSI Biophysics.

ESA-FAIR co-operation

GSI has been selected by ESA as the European facility to run the ground-based space radiation research study (Investigations on Biological and Physical Effects of Radiation; IBPER). In fact, with the current exploration plans, cosmic rays represent a major health risk, not only for cancer but also for the central nervous system [1]. A large experimental campaign with ^{56}Fe-ions (12.5

shifts) has been completed in 2025 to serve the experiments selected within the ESA-IBPER project (AO-IBPER-22, now closed). The ESA-PAC selected the new proposals to be implemented in 2026-27 in the frame of the new AO-IBPER-24. the PAC selected 10 proposals led by investigators from UK, Germany (2), Austria, Italy (3), Poland and Czech Republic (2). The proposals will use a total of 20 shifts in 2 years. Investigators will use protons, Fe-ions, Ne-ions and the GSI GCRsim. The IBPER Investigators' Working Group meeting was held at GSI on December 1 to prepare the first run in 2026.

Moreover, we organised the 5th edition of the ESA-FAIR Summer School with 16 students from all over the world studying and working on space radiation protection at ESOC and GSI in Darmstadt. Students selected were from Germany (2), Italy (2), Switzerland, Belgium (2), Canada, Poland, UK (2), Ireland, Spain (2), The Netherlands, Hungary, plus 3 auditors from GSI. The school was a great success, with a very prestigious faculty including two astronauts (Thomas Reiter and Christer Fuglesang) and the former ESA DG Jan Wörner. Along with Piers Jiggens, responsible for radiation studies at ESA, they visited the FAIR construction site during the school (Figure 16).

Figure 16: Visit to the FAIR construction site of astronauts and ESA representatives on August 26. Dr. Thomas Reiter, ESA astronaut from Germany and former ESA-Director for Satellite Operation and Human Spaceflight, and Professor Christer Fuglesang, ESA astronaut from Sweden and director of the KTH Space Center participated in the visit. Professor Johann-Dietrich Wörner, former ESA Director General and Space coordinator of the Hessian state government, and Dr. Piers Jiggens, Science Lead of Radiation at ESA, were also among the guests. The guests were welcomed by Professor Thomas Nilsson, Scientific Managing Director of GSI and FAIR, Dr. Katharina Stummeyer, Administrative Managing Director of GSI and FAIR, and Jörg Blaurock, Technical Managing Director of GSI and FAIR. Many leading experts from GSI/FAIR's departments also participated. Photo: Ingo Peter, GSI/FAIR.

Awards

- Marco Durante received the „BIR Medal for Outstanding International Achievement" for outstanding international achievement. The award ceremony took place on March 7 during the Annual Congress of Radiotherapy and Oncology of the British Institute of Radiology (BIR) in London. Marco Durante's award talk can be watched on the BIR YouTube page.
- Cristina Totis, Ph.D. in biology with a thesis in radioimmunology performed at GSI supervised by Claudia Fournier, was awarded the Christoph Schmelzer prize 2025.
- Four Ph.D. students enrolled at TUDa and working at the GSI Biophysics (Amèlia Jansen van Vuuren, Luca Lunati, Peter Dick and Malte Benje) received the "Giersch Excellence Award 2025" from the HGS-Hire Graduate School for their outstanding scientific work during their ongoing Ph.D.
- Michael Scholz, former group leader at GSI Biophysics, received the Ulrich Hagen award 2025 from DeGBS.

Grants

- Marco Durante received an ERC advanced grant of 2.5 M€ in 5 years to study a new potential cure for brain cancer. The proposal, called Heavy-Ion FLASH (HI-FLASH), will study the effect of Ne-ions at ultra-high dose rate in the normal brain and in glioblastoma in a rat model. The project is slated to start in April 2026, at the end of the previous ERC AdG of Marco Durante (ERC BARB).
- Katja Kratz received a BMFTR grant (MUTRAD) to study DNA repair after heavy ion irradiation (828 k€, 4 years).
- GSI Biophysics (Daria Boscolo and Thomas Friedrich) is a partner of the EURATOM project PRESTO, funded in 2025 to study proton minibeam radiation therapy (274 k€, 4 years).
- The Ph.D. student Malte Benje won a PTCOG Biology Grant 2025 of 14 k€ (1 year) for a study on circulating tumor cells in radiotherapy
- Insa Schröder got two grants: one from Carl Zeiss Stiftung (198 k€, 5 years) and another from BMWE (ZIM-Program, 214 k€ in 3 years) for studying radiation effects in organoids

Highlights in 2025

This year was exceptionally productive for the Biophysics Department, with 40 peer-reviewed papers in the repository. A few highlights are provided below.

Radioactive ion beams in cancer therapy

The ERC grant BARB, performed in collaboration with the Fragment Separator (FRS) Department in NuSTAR and the Ludwig-Maximilian Universität (LMU) in Munich, has published in 2025 the most important result - the first treatment of a tumour in vivo with radioactive ion beams. The paper in *Nature Physics* [2] demonstrates the successful treatment of osteosarcoma tumours implanted in the neck of C3H mice, very close to the spinal cord, using high-energy ^{11}C-ion beam. The positrons, emitted by the ^{11}C beam, annihilate with electrons, and the resulting photon pair was detected with a small animal PET detector built by LMU. Figure 17 shows an online image of the activity map overlapped to the CT scan of the mouse. Thanks to the unique online image guidance, we could control the tumour with a very low toxicity in the spinal cord. This proof-of-principle paves the way to possible clinical applications of radioactive ion beams.

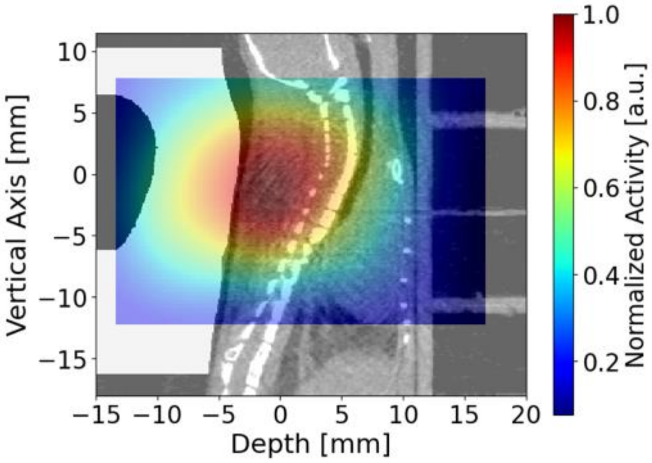

Figure 17: PET imaging of the ^{11}C activity recorded during the treatment of a tumour in the neck of a mouse, very close to the spinal cord. Images from Ref. [2], reproduced under CC-BY 3.0 license.

Human organoids unveil the mechanism of radionecrosis

The project led by GSI in in collaboration with MD Anderson and funded by the US National Institute of Health (NIH) could demonstrate the mechanism of brain radionecrosis that is caused by particle therapy more frequently than X-rays, representing a concern for the treatment of paediatric brain tumours. Using human cerebral organoids (mini-brains), we were able to show [3] that the lesions observed in brain MRI scans after radiotherapy are not due to the death of brain cells (brain necrosis), as generally stated. Rather, they are caused by abnormal generation of choroid plexus-like cells lining liquid-filled cavities (Figure 18). The choroid plexus is responsible for the production of cerebrospinal fluid and is for example involved in detoxification processes of the brain. Therefore, the observed cavities indicate excessive fluid production. This new mechanism suggests new pharmaceutical countermeasures against these adverse events in the brain of the patients.

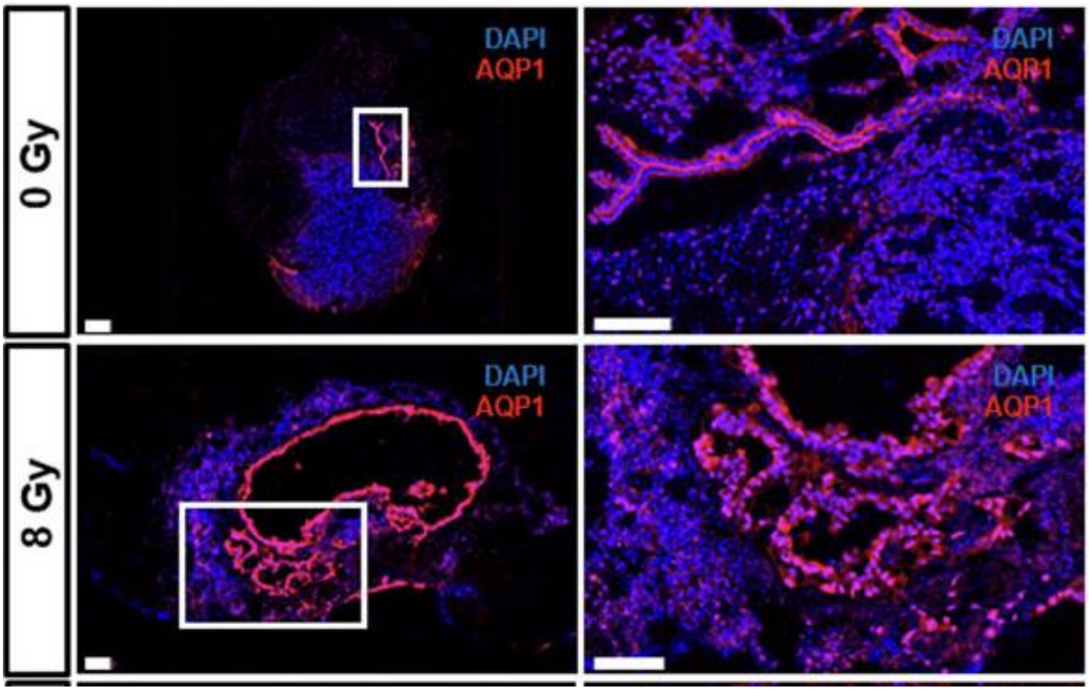

Figure 18: Representative immunofluorescence stainings of the choroid plexus marker AQP1 (red; nuclei stained with DAPI in blue) in control and irradiated human cerebral organoids (protons, 8 Gy). Scale bar = 100 µm. Images from Ref. [3] reproduced under CC-BY 3.0 license.

FLASH Bragg-Peak Irradiation with carbon ions

In recent years, ultra-high dose rate (UHDR) irradiation has emerged as a promising innovative approach to cancer treatment. Characteristic feature of this regimen, commonly referred to as FLASH effect, demonstrated primarily for electrons, photons, or protons, is the improved normal tissue sparing, whereas the tumour control is similar to the one of the conventional dose-rate treatments. The FLASH mechanism is, however, unknown. One major question is whether this effect is maintained when using densely ionizing (high-LET) heavy nuclei. Using our specialised beamline in Cave A (Figure 19) we could demonstrate sparing of the healthy tissue with unchanged tumour control in a mouse model of osteosarcoma irradiated with accelerated carbon ions in the Bragg peak at UHDR [4]. This marks the first evidence of FLASH effect for densely ionizing radiation and supports the use of UHDR in heavy ion therapy.

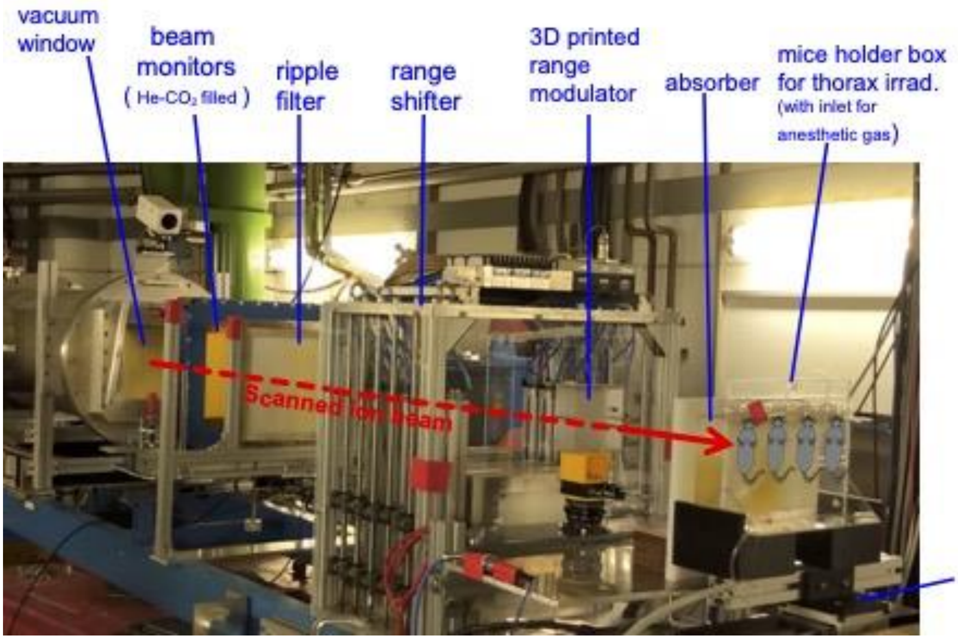

Figure 19: Beamline in Cave A for ultra-high dose rate experiments with heavy ions. Photo by Uli Weber, GSI.

Outlook 2026

The beamtime in 2026 will be extremely important for the two ERC grants running at GSI (PROMISE and HI-FLASH). PROMISE will use a mixed C/He beam, and HI-FLASH will instead study Ne-ions at UHDR. We will also offer the first IBPER beamtime to the new investigators. In August, we will host the 6th edition of the ESA-FAIR Summer School, which will be directed for the first time by Dr. Charlot Vandevoorde.

Selected publications of 2025

[1] F. L. Wuyts, C. Deblieck, C. Vandevoorde, and M. Durante, "Brains in space: impact of microgravity and cosmic radiation on the CNS during space exploration," *Nature Reviews Neuroscience*, vol. 26, no. 6, pp. 354–371, June 2025, doi: 10.1038/s41583-025-00923-4.

[2] D. Boscolo *et al.*, "Image-guided treatment of mouse tumours with radioactive ion beams," *Nature Physics*, vol. 21, no. 10, pp. 1648–1656, Oct. 2025, doi: 10.1038/s41567-025-02993-8.

[3] T. Bender *et al.*, "Aberrant choroid plexus formation drives the development of treatment-related brain toxicity," *Communications Biology*, vol. 8, no. 1, p. 276, Feb. 2025, doi: 10.1038/s42003-025-07736-2.

[4] W. Tinganelli *et al.*, "FLASH Bragg-Peak Irradiation With a Therapeutic Carbon Ion Beam: First In Vivo Results," *International Journal of Radiation OncologyBiologyPhysics*, vol. 121, no. 5, pp. 1282–1292, Apr. 2025, doi: 10.1016/j.ijrobp.2024.11.089.

3. Research of the Compressed Baryonic and Quark Matter Departments

Coordination: Prof. Dr. Joachim Stroth (Goethe University Frankfurt, Helmholtz Institute & GSI)

3.1 Executive summary

Authors: Tetyana Galatyuk, Silvia Masciocchi, Joachim Stroth

The departments conduct relativistic to ultra-relativistic heavy-ion and proton-proton collisions to investigate the emergence of matter and its properties under extreme conditions governed by QCD in the non-perturbative regime. In 2025, the three departments that serve as (German) host laboratories for the three major experimental collaborations ALICE at CERN, CBM at FAIR, and HADES at GSI achieved significant milestones in advancing the scientific objectives of the heavy-ion and hadron physics program.

The **ALICE** group at GSI made a major contribution to the LHC Run 3 physics program with the successful commissioning and operation of the GEM-based Time Projection Chamber (GEM-TPC). This represents a key upgrade to the central tracking detector, allowing for continuous readout under high-luminosity conditions. The GSI team played a central role in the deployment, calibration, and data-taking phases, enabling the first high-statistics measurements of QCD matter in the new operational mode. Concurrently, the GSI ALICE group has maintained its successful investigation of heavy-flavour production in heavy-ion and proton-proton collisions, with a particular focus on leptonic and semi-leptonic decay channels. Notably, a surprising observation has emerged, indicating that the hadronization of charm quarks appears to be influenced by the surrounding environment. This finding was corroborated by comparing the results obtained from lepton-induced reactions with (purely hadronic) proton-proton interactions studied by ALICE.

In anticipation of the commencement of SIS100 operations, the **CBM** collaboration redirected its focus from development and prototyping to large-scale construction. This shift coincided with the commencement of mass production of SIS100 detector components. The GSI group, in particular, concentrated on the production of ladder modules for the Silicon Tracking System (STS). By the conclusion of the year, 328 modules had been manufactured, and the observations pertaining to yield and quality were the subject of a production readiness review. The GSI CBM team spearheads the initiative to guarantee the timely delivery of hardware and system integration, as well as the development of software and firmware necessary for operating CBM in free streaming mode. Testing of components within the miniCBM setup has been ongoing, with the objective of achieving a comprehensive demonstration of the online feature extraction capability.

The **HADES** collaboration could successfully complete the Au+Au beam energy scan. After the successful repair of the cryogenic system, HADES took data for nine days end of April beginning of May 2025. With the reduced dead time of the DAQ system due to the exchange of the MDC's front-end electronics (Plane I and II) and the again excellently operating Spill Optimisation System used in conjunction with knock-out extraction, the anticipated data volume for nine days based on the proposal could be surpassed by about a factor two. This added another 6 billion events on disk for four different energies (0.8, 0.6, 0.4 and 0.2 GeV/u). This run completes the search for signs of novel forms of matter and targets the region in the QCD phase diagram where the critical point of the liquid-gas phase transition is conjectured. To boost the discrimination power of the high statistics data samples for heavy-ion reactions taken with HADES, the new time-differential efficiency correction method has been implemented accounting for beam intensity fluctuations and related fluctuations of flux due to delta-electron emission of non-interacting ions passing the target stack. The spectrometer is now being reconfigured to be ready for pion beam whenever the conditions are such that sufficient intensity can be provided by the accelerator complex after the fire.

Together, these achievements underscore the pivotal role of GSI in driving experimental innovation and delivering critical infrastructure for FAIR and CERN-based heavy-ion and hadron physics research.

3.2 ALICE at GSI

Head: Prof. Dr. Silvia Masciocchi (Heidelberg University and GSI), Dr. Ralf Averbeck (GSI)

Authors: Ana Maria Marin Garcia, Dariusz Miśkowiec

Introduction

ALICE is a major high-energy experiment at the CERN Large Hadron Collider (LHC), dedicated to the study of the quark-gluon plasma created in collisions between lead nuclei. In April 2025, more than 13,000 researchers from ALICE, ATLAS, CMS and LHCb experiments at CERN were honoured with the Breakthrough Prize (https://breakthroughprize.org) in Fudamental Physics "for the exploration of nature at the shortest distances and most extreme conditions". The prize money of $500,000 will be used to offer grants for doctoral students from the collaborations' member institutes to spend research time at CERN. GSI is among the most important of the 141 institutions currently authoring ALICE publications. The newly elected spokesperson of the ALICE collaboration and two other members of its Management Board are from GSI.

As a part of the LHC Run 3 (2022-2026), from May till October of 2025 ALICE was measuring proton-proton collisions at $\sqrt{s}$ = 13.6 TeV. In November and December came the most crucial part of the 2025 running, namely 21 days of Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV. The Pb-Pb interaction rate was leveled at 23 kHz. The proton and lead collision campaigns this year were complemented by very successful short runs with light ions: proton-oxygen, oxygen-oxygen, and neon-neon. In addition, low magnetic field proton-proton and lead-lead collisions dedicated to the measurement of electron pairs have been measured.

In parallel to data taking, in 2025 ALICE published 33 articles. In the following we briefly discuss selected results from these papers and from ongoing analyses.

Selected highlights in 2025

Two-particle correlations involving more and more exotic hadron species are a field of vigorous activity in ALICE. Newly published correlations between pions and deuterons measured in pp [1] and Pb-Pb [2] collisions are shown in Figure 20 and Figure 21, respectively. The correlation function is defined as the number of pion-deuteron pairs, normalised to pairs from event mixing where the two particles are taken from two separate collision events. The ordinate k* is the relative momentum between the two particles. The Coulomb interaction is manifest at the small relative momenta, k* < 50 MeV/c. In addition, the pp collision data show a bump coming from Δ decay. The picture here is as follows. A Δ-resonance decays into a pion and a proton (neutron). If the proton (neutron) velocity matches the velocity of a neutron (proton) passing by, they may coalesce and form a deuteron. The pion assists their fusion by carrying away the excess momentum. It turns out that the majority of deuterons produced at the LHC is created this way [1].

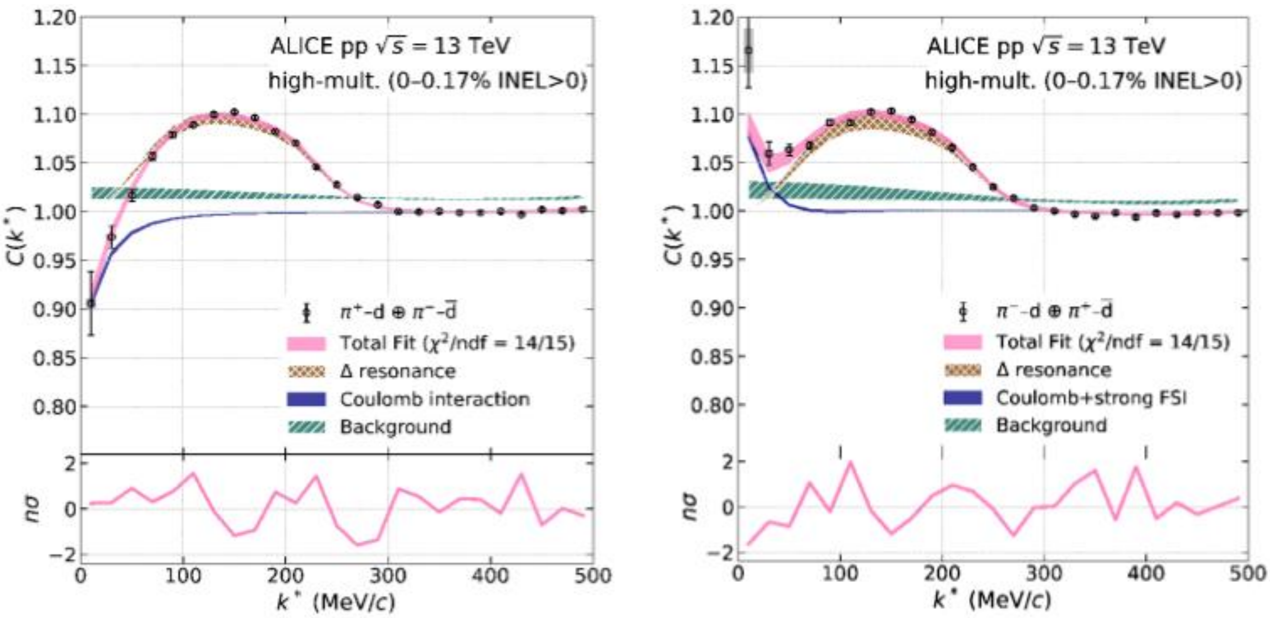

Figure 20: Like-sign (left) and unlike-sign (right) pion-deuteron correlation functions measured by ALICE in high-multiplicity pp collisions at 13 TeV. At relative momentum k* < 50 MeV/c, effects of the Coulomb interaction are visible. The bump between 50 and 300 MeV/c is the **Δ**-resonance. Figure from [1].

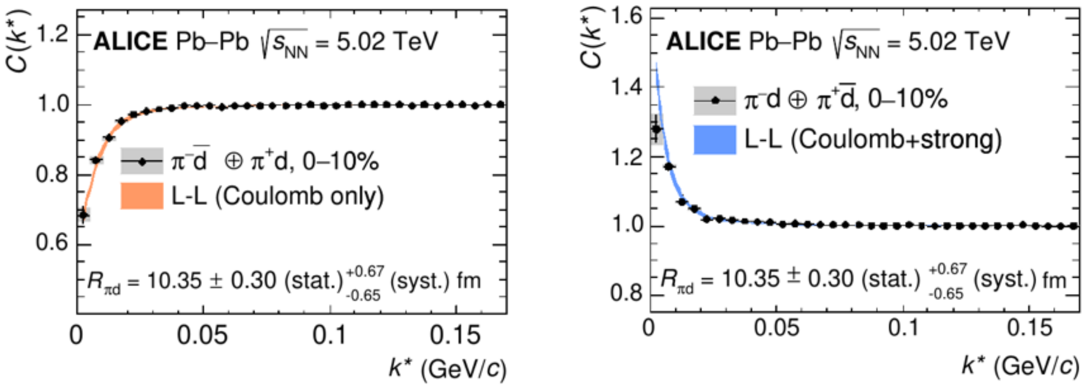

Figure 21: Like-sign (left) and unlike-sign (right) pion-deuteron correlation functions measured by ALICE in central Pb-Pb collisions at 5.02 TeV. The correlations are dominated by the Coulomb interaction. Figure from [2].

This is analogous to the gravitational clustering of matter in the universe, where the (angular) momentum of two clumps approaching each other is carried away by photons. The reason why the Δ-resonance bump is not seen in Pb-Pb is the large combinatorics. There exist two categories of effects causing deviations of the correlation function from unity. The first group are those interactions that are present for every pair in the event. To it belong the Coulomb interaction and the quantum statistics effects, as well as, on the apparatus side, the two-track resolution. The second category are the interactions involving only two particles - these are the strong interactions and in particular resonances. When going from low to high multiplicities, the first group of effects stays constant, the second gets diluted by combinatorics. The mean charged-particle multiplicities in the data samples in Figure 20 and Figure 21 are, respectively, 31 and 1800 charged particles per unit pseudorapidity. The Δ-resonance bumps visible in Figure 20 are thus reduced in magnitude in Figure 21 by a factor of 1800/31 = 60.

The Δ-resonance is not the only short-lived resonance appearing in correlation functions at the LHC. Several hadrons stable against strong interactions have excited states, which decay to the ground state and (usually) a pion. Since such excited hadrons typically have lifetimes within 1-50 fm/c, on one hand they effectively enlarge the particle-emitting source. On the other hand, their mass and/or width might be modified in the high-density environment. Last but not least, their yields are sensitive to the duration of the hadronic rescattering phase: the long-lived ones will have a higher chance to escape from the fireball than the short-lived ones, whose decay daughters may rescatter. ALICE has measured $K^*(892)$ ($c\tau$ = 4 fm), $\phi(1022)$ (46 fm), $\Lambda^*(1520)$ (13 fm), $\rho(770)$ (1.3 fm), $\Xi(1530)$ (22 fm), $\Sigma(1385)$ (5.4 fm), $f_1(1285)$ (8 fm), $D_{s1}(2536)$ (210 fm), $D_{s2}(2573)$ (12 fm), $\omega(782)$ (23 fm), and $D^*(2010)$ (2.4 fm) in pp and/or Pb-Pb collisions of various centralities. With increasing statistics, more and more exotic particles are coming into reach. In a recent analysis by ALICE [3], the $\Omega(2012)$ baryon was identified and its transverse-momentum spectrum was measured (Figure 22). This is the first observation of this resonance at the LHC. The mass and width are consistent with the measurement by the Belle experiment, which discovered this particle in 2018.

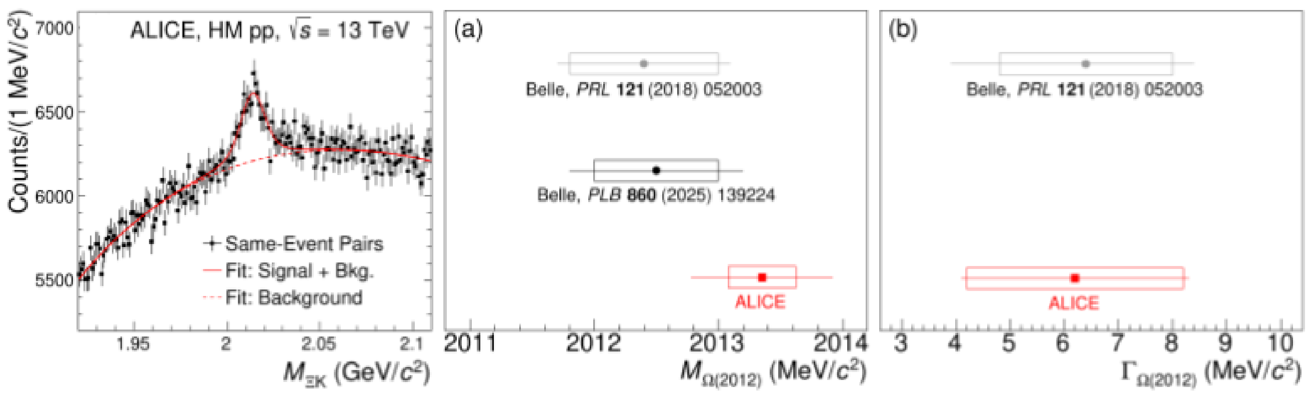

Figure 22: The $\Omega(2012)$ resonance measured by ALICE in the $\Xi\bar{K}$ decay channel. The measurement corroborates the discovery of this particle by Belle in 2018. Figure from [3].

The analysis of the Λ_c lifetime measurement is another project aiming at a precise determination of properties of exotic particles. This is one of the studies driven by the members of the ALICE group at GSI. The analysis was developed and tested on Monte Carlo data. It will be performed using the high-statistics data from the still ongoing Run 3 and possibly also applied to other charmed baryons.

The GSI team is also pursuing the analysis of correlations in another exotic combination of species, namely proton and J/ψ. The strong interaction between these two particles happens via exchange of multiple low-energy gluons. Therefore, it is sensitive to the gluon distribution in protons and important for the understanding of pentaquarks.

In 2025, the LHC for the first time in its history provided beams of neon and oxygen nuclei. A few days of stable beams were sufficient for several important measurements. The first analysis of the elliptic and triangular flow in oxygen-oxygen and neon-neon collisions at LHC energies [4] is shown in Figure 23.

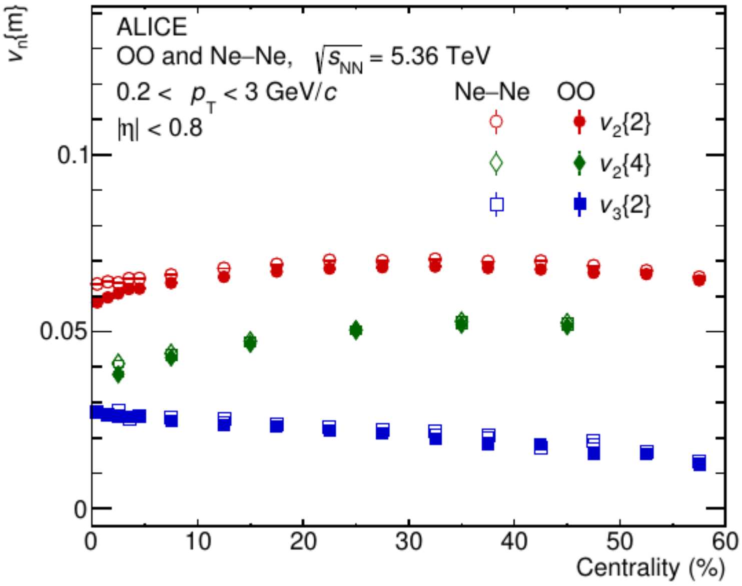

Figure 23: Elliptic (v_2) and triangular (v_3) flow of charged particles in oxygen-oxygen (solid markers) and neon-neon (open markers) collisions of various centralities at 5.36 TeV. Vertical lines and open boxes represent, respectively, statistical and systematic uncertainties, most of them being smaller than the symbol size. Figure from [4].

Upgrades

The longstanding involvement of GSI in the hardware of the ALICE experiment is continued in works related to the new inner tracking system ITS3 to be installed in ALICE in 2026-2030, and to the design and construction of a completely new silicon-only heavy-ion experiment at the LHC (ALICE 3) in 2034. To this end, 30 detector tests at the accelerator beams at GSI, DESY, CERN PS and SPS, COSY (Jülich), INP (Kraków), MIT (Marburg), and ELSA (Bonn) have been performed since 2019. The year 2025 saw three tests: material budget imaging at DESY, particle identification with ALPIDE at GSI, and measurements and alignment studies of Analogue Pixel Test Structures at ELSA. The setup used in the latter is shown in Figure 24. The test results are discussed in two recent publications [5] and [6].

Figure 24: Setup for a test towards the Outer Tracker of ALICE 3, performed in the electron beam from ELSA Bonn in November 2025. The detector to be tested is sandwiched between several layers of conventional detectors. The assembly was irradiated by a beam of charged particles.

In 2025 the PANDA Technical Coordination team got involved with the ALICE 3 pixel project with the long-term aim to acquire knowledge for modernization of the detector concept of the PANDA experiment along the lines of the very innovative setup of

ALICE 3. The PANDA team took up the development of a modularised air-cooling channel for the ALICE 3 silicon pixel-based Outer Tracker, in which the ALICE department is involved. Prototyping was performed with the help of 3D printers, and a complete stave was assembled at Heidelberg University with cooling channels on a carbon fibre spaceframe (Figure 25). The cooling structure is tested at a dedicated lab at TU Munich.

Figure 25: Left: Prototype air-cooling channel with air inputs/exits and flow return. Right: Fully assembled stave with two cooling channels on a carbon-fiber spaceframe.

Selected publications of 2025

[1] S. Acharya et al., “Observation of deuteron and antideuteron formation from resonance-decay nucleons,” Nature, vol. 648, no. 8093, pp. 306–311, 2025, doi: 10.1038/s41586-025-09775-5.

[2] S. Acharya et al., “Accessing the deuteron source with pion-deuteron femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV,” Phys. Rev. C, vol. 112, no. 6, p. 064003, 2025, doi: 10.1103/mrp4-z4hh.

[3] S. Acharya et al., “Observation of the Ω(2012) baryon at the LHC,” Phys. Rev. D, vol. 112, no. 9, p. 092002, 2025, doi: 10.1103/v4mh-3r8z.

[4] I. J. Abualrob et al., “Evidence of nuclear geometry-driven anisotropic flow in OO and Ne-Ne collisions at $\sqrt{s_{NN}}$ = 5.36 TeV,” Sept. 2025, Available: https://arxiv.org/abs/2509.06428

[5] G. A. Rinella et al., “Further characterisation of Digital Pixel Test Structures implemented in a 65 nm CMOS process,” Nucl. Instrum. Meth. A, vol. 1083, p. 171082, 2026, doi: 10.1016/j.nima.2025.171082.

[6] O. Abdelrahman et al., “Characterisation of the first wafer-scale prototype for the ALICE ITS3 upgrade: The monolithic stitched sensor (MOSS),” Nucl. Instrum. Meth. A, vol. 1086, p. 171297, 2026, doi: 10.1016/j.nima.2026.171297.

3.3 CBM at FAIR

Head: Prof. Hans Rudolf Schmidt (GSI & University of Tübingen)

Authors: Piotr Gasik, Peter Senger, Johann Heuser, Makysm Teklishyn (GSI)

Highlights & Activities in 2025

Status of Cave Civil Construction and Infrastructure

In 2025, several important milestones in civil construction were reached. The second crane in the entry hall has been installed and commissioned, the access road to the building has been completed, and the final backfilling with soil around the building has been finished. With these steps, the main civil construction activities related to the CBM cave and its surroundings can now be considered largely completed, providing stable conditions for the next phases of technical and detector installation (see Figure 26).

At the same time, significant progress was made in infrastructure planning and preparation. The CBM cave infrastructure activities gained momentum, driven by the advancing preparation of the Technical Building Infrastructure (TBI) engineering and the associated execution planning. This enabled the collaboration to resume and intensify previously postponed activities, in particular the harmonization of experiment and building installations, as well as the continued development of infrastructure concepts, cable routing, and integration layouts. A major setback, however, was the postponement of the formal TBI approval. This delay affects parts of the execution planning and introduces additional uncertainty into the installation schedule. Nevertheless, the collaboration continues to push forward with preparatory engineering, coordination, and detailed planning wherever possible, ensuring readiness to proceed rapidly once the TBI decision is granted.

In alignment with the CBM dipole installation schedule, major efforts were directed toward completing the upstream infrastructure. The magnet foundation has been cast in concrete inside the building, and procurement of the shielding concrete slabs for the Upstream Platform (UP) was initiated. In parallel, the steel cryogenic platform has been ordered and is currently under production. During the second half of 2025, substantial work was invested in finalizing the static calculations for the UP. A final version was submitted at the end of the year and is currently awaiting approval by the official FAIR structural authority. The tender for the cladding concrete was awarded to FABER & SCHNEPP; however, the start of production has been slightly delayed due to remaining technical clarifications. Installation of the concrete blocks is planned to be carried out by a contractor already active on the FAIR construction site. Once the concrete blocks are mounted, installation of the cryogenic platform will follow, and subsequent steps will include the procurement of handrails and stairs, which will conclude the UP installation.

Figure 26: CBM Cave in 2025

At the same time, several other infrastructure components are advancing. The primary cable database has been established and continuously updated, together with the inventory of racks, crates, and modules, ensuring readiness for the detailed engineering of the building infrastructure. The CBM Collaboration has also revised its overall infrastructure planning in anticipation of the future TBI approval. The rail system (RS) project documentation is being updated and discussed with the detector subsystems before launching the tender.

On the integration side, several changes in detector planning required adjustments to the infrastructure layout. The replacement of the originally foreseen Russian in-kind Projectile Spectator Detector (PSD) by the Forward Spectator Detector (FSD) led to a redesign of the beam pipe section passing through the experiment, as the geometry and integration constraints of the new system differ substantially. The main improvement concerns the modification of the beam pipe shape, which is changed from a straight cylindrical design to a conical one. This adaptation helps to minimize background at the FSD location and is expected to significantly enhance its performance, in particular for reaction plane determination and centrality measurements. At present, the detailed engineering of the beam pipe is ongoing, including vacuum system calculations and the design of the corresponding support structures.

The CBM Superconducting Magnet

The CBM superconducting dipole magnet provides a vertical magnetic field with a magnetic field integral of 1 T.m, which is needed to obtain a momentum resolution of $\Delta p/p \approx 1\%$ for track reconstruction at FAIR beam energies. The magnet gap has a height of 147 cm and a width of 330 cm, allowing the accommodation of the STS detector system with a polar-angle acceptance of ±25° and a horizontal acceptance of ±30°. The total weight of the magnet is approximately 160 t.

A liquid-helium thermosiphon system is used to cool the coils. It consists of a vessel containing liquid Helium at a temperature of 4.6 K, located inside the feeder box above the two coils. The operating principle of a thermosiphon is based on the natural circulation of helium within the system. The flow is driven by the density difference between the heated fluid, containing a gaseous component in the return line, and the colder fluid in the supply line. The circulation can be additionally supported by a heater in the return line.

A passive quench protection system in the form of cold rectifier diodes is foreseen for the CBM magnet coils. Each coil is subdivided into four sections, with each section protected by four pairs of back-to-back diodes. This redundant diode configuration accounts for two possible diode failure scenarios in both current directions.

The mechanical support structure of the coils must securely fix the coils and compensate for the Lorentz force, which is equivalent to approximately 300 t, while simultaneously minimizing heat transfer between the cold mass of the coils (at liquid-helium temperature) and the coil cryostat at room temperature. This support structure is realised using six tension rods and twelve bushings. The tension rods fix the coils in position, while the bushings compensate the compressive component of the Lorentz force.

The magnet will be delivered by Bilfinger Nuclear & Energy Transition GmbH (BNET) in Würzburg. In 2025, the Final Design Reports for the yoke, the magnet support structure, and the coils, including the support and cooling system, were approved by GSI. The Final Design Report for the Branch Box and the Transfer Line to the magnet is scheduled to be finalised at beginning 2026. In September 2025, the Factory Acceptance Test of the magnet support structure and alignment system was successfully performed (see Figure 27). In addition, the test of a coil-support bushing was completed successfully. The winding and impregnation of two coils have been completed, and the construction of the yoke and the feeder box is currently ongoing. The Factory Acceptance Test of the complete magnet is planned for Fall 2026.

Figure 27: Teams of GSI and BNET participating in the Factory Acceptance Test of the magnet support and alignment structure.

Status of STS Module and Ladder Assembly and Testing

At the core of the realization of CBM's central detector for charged particle detection and momentum measurement, the Silicon Tracking System, is the series production of so-called detector modules and ladders, functional building blocks of double-sided silicon microstrip sensors, ultra-thin cables and front-end electronics to populate the tracking stations. They are required in numbers of many hundreds, with almost each of them being of an individual variant of the same base design, a consequence of the stationary-target concept of the CBM experiment.

Since summer 2023, a full "machinery" of laboratory infrastructure, dedicated teams of technical and scientific staff, and logistical procedures for the distribution of material, logging of in-assembly test results and interim storage has been brought up to operation. Two assembly sites, GSI and KIT, share the module assembly tasks in specially prepared clean rooms, following a many-step bonding and quality check list. The modules are received back at GSI in dedicated laboratory space for the final qualification and acceptance test. This task involves strong engagement of students. Accepted modules are passed on to the ladder assembly team where they are arranged on low-mass carbon fibre support structures, the objects to be integrated into the detector system on higher levels forming the tracking stations. During the assembly process, every module is checked for voltage holding capability before the next module is added to the ladder. Geometrical survey of the completed ladders, determining in a contactless optical procedure the precise location of the sensors in space, is the base for forthcoming detector alignment in the system integration and commissioning procedure [1].

The quality acceptance of the ladders is done by a team dedicated to the task of full calibration and operation on two test stations equipped with prototype or final powering and readout infrastructure. Testing keeps up closely with the ladder production. All qualification results on the modules and ladders are documented as they will be essential for the system assembly and commissioning.

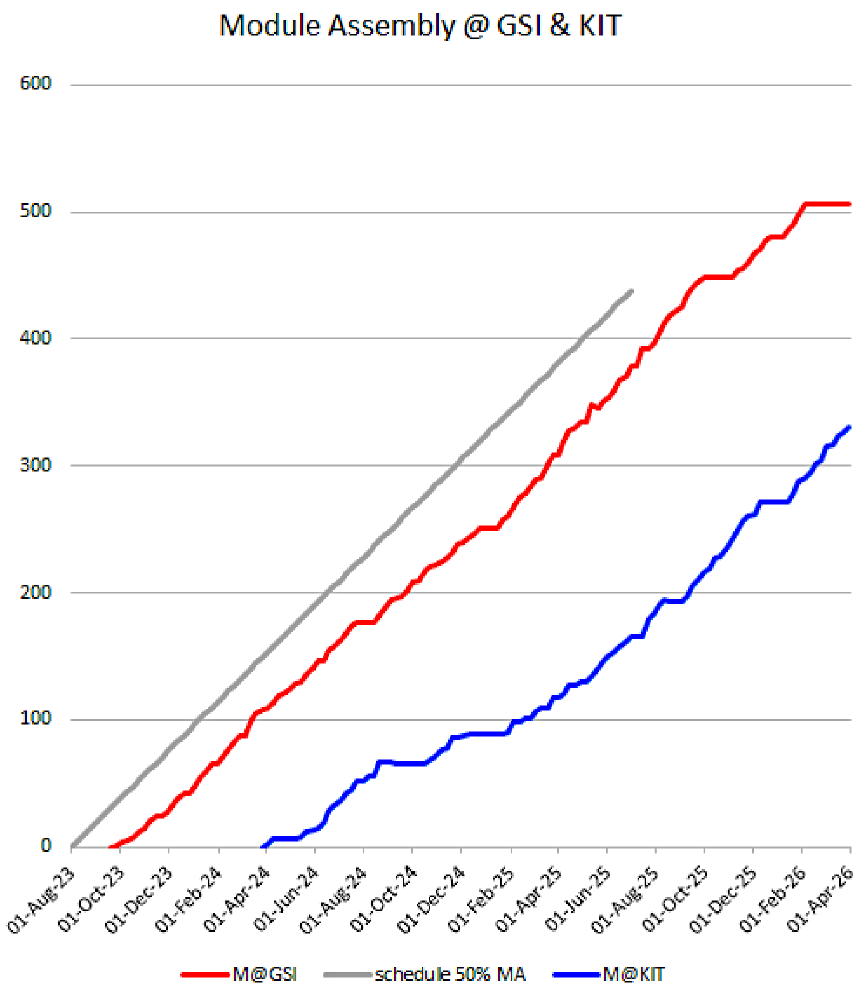

Figure 28: Module production rate at the assembly centres GSI (red) and KIT (blue). The grey line represents the reference slope.

As of January 2026, the series production has progressed to 90% of the required 876 modules (see Figure 28). About 5% of them did not match quality cuts according to different criteria in the final inspection, despite of the various quality checks at manufacturing. They were rebuilt, using extra material available for such cases. Ladder assembly was brought to speed at installations in the GSI clean room after a technical review of the pre-production in December 2024. At the beginning of 2026, 30% of the required 106 ladders were fully assembled (see Figure 29). As the dominant time constant during ladder assembly is the curing of glue, a second ladder assembly line and second team was established in 2025. Some personnel from GSI module assembly were shifted to this task, which became possible as the GSI assembly share of modules, half of the total, was close to be reached. Throughput may thus double to about 1.1 ladders/week average

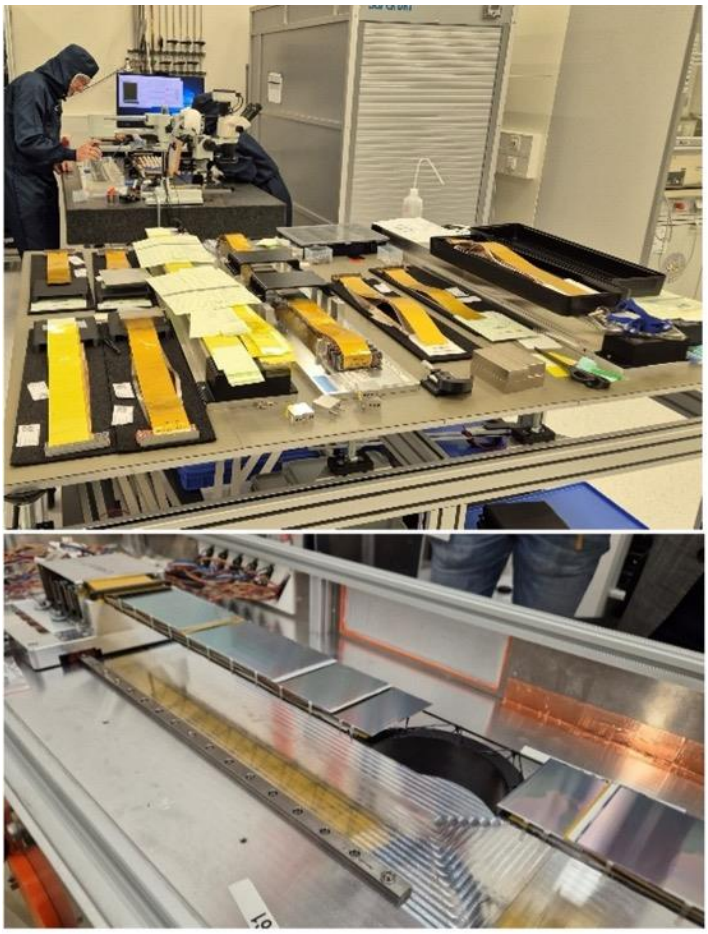

Figure 29: Ladder assembly at GSI (top). A finalised ladder with central cut-out for the beam pipe mounted in the qualification test stand.

Half Unit Integration and Test Infrastructure Development

The Half Unit represents the largest mechanical structure integrated into the STS enclosure [2][3]. It constitutes the final integration level before installation into the detector volume. Each Half Unit consists of a precision-machined aluminium support frame hosting the powering and readout electronics, as well as the fully equipped ladders carrying silicon sensors and front-end boards (FEBs). In total, 20 Half Units will be produced for the Silicon Tracking System (see Figure 30). This number defines the scale of the required infrastructure, logistics, quality assurance, and production workflow.

In 2025, the focus was placed on completing the preparatory work necessary to enable controlled and reproducible series assembly (see Figure 31). This included consolidation of the mechanical integration concept, validation of handling and alignment procedures, preparation of the electrical integration scheme, and commissioning of the corresponding test infrastructure. In a second half of the year, a mechanical and semi-functional prototyping of the first Half Unit, U3DL, was carried out. This prototype served as a full-scale validation platform for mechanical integration, services routing, and partial functional verification.

The aluminium support frame was equipped with fully functional cooling plates, allowing verification of mechanical tolerances, mounting procedures, and service accessibility. Readout Boards (ROBs) including their cooling bodies were installed to assess spatial compatibility and thermal interface constraints. In addition, Powering Boards (POBs) for both FEB chains and ROBs were mounted in their designated positions.

A complete cabling and wiring exercise was performed. This included mechanical routing of low-voltage, high-voltage, and data connections, as well as verification of strain relief, bending radii, and service accessibility under realistic boundary conditions.

A critical integration challenge was identified in the routing of data cables between FEBs and ROBs. Unlike power cables, which can be adjusted and trimmed during installation, data cables must be procured in predefined lengths. Therefore, precise determination of required cable lengths and routing paths was essential. Through the prototyping exercise, the necessary cable geometries and length specifications were defined and documented for procurement. The prototyping campaign provided validated mechanical layouts, confirmed service routing strategies, and reduced integration risks for series production.

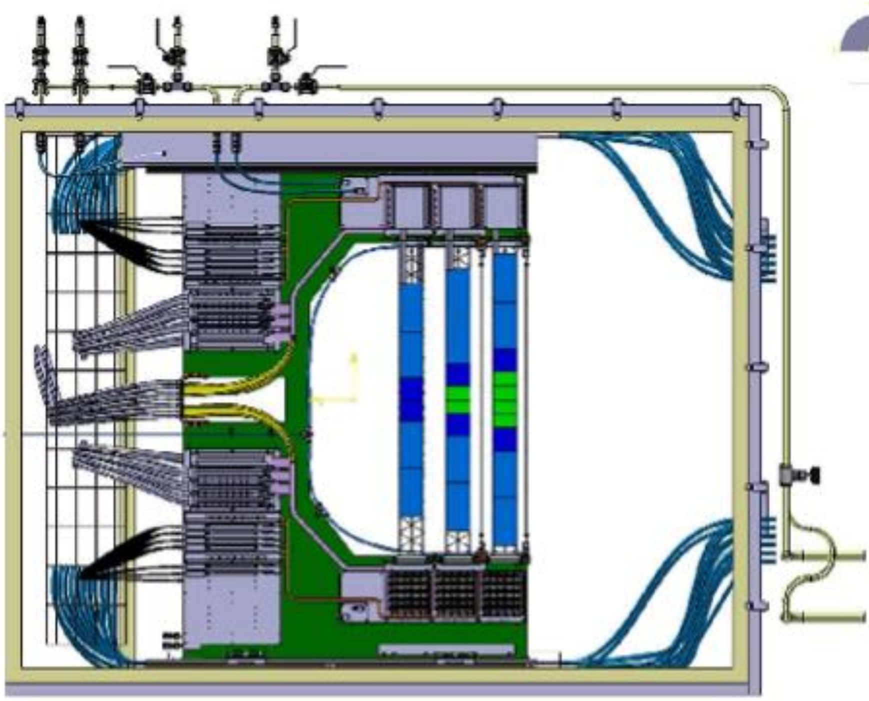

Figure 30: CAD Drawing of an STS Half Unit.

Figure 31: Prototype STS Half Unit on its Assembly Turntable.

In parallel to the U3DL prototyping, the laboratory infrastructure required for series Half Unit assembly and testing was further developed and consolidated. Dedicated assembly and transportation stands were designed and commissioned to ensure reproducible positioning, safe handling, and controlled movement of the Half Units between integration and test areas. In addition, a dedicated Half Unit cold box was prepared for system-level thermal and functional tests under controlled environmental conditions. Complementary peripheral setups were established for standalone component tests, in particular for ROB and POB verification prior to integration.

In preparation for silicon detector integration, the STS laboratory is being upgraded to improve environmental cleanliness. A dedicated integration area for Half Units is being equipped with a HEPA filtration unit to reduce airborne particulate contamination during assembly.

Several large-scale infrastructure elements reached an advanced stage of implementation in 2025. The readout chain based on CRI electronics was deployed and integrated into the laboratory environment. Power and high-voltage distribution systems were installed, including structured cabling and patch-panel infrastructure within the STS laboratory. Furthermore, the cooling plant located in the C17 container was prepared to support Half Unit operation under realistic thermal loads.

A decision was taken in 2025 concerning changing the coolant for cooling down the electronics. Originally, the system was planned for operation with a NOVEC 649 engineered liquid. The latest re-evaluation on the information on safety of such substance from October, 2024 introduced a new hazard for this liquid: H361d, suspected of damaging the unborn child.

Together with well-known proposed restrictions on PFAS by the European Chemical Agency (ECHA) and cost, it makes reliance on such media incompatible with long-term operation and planning security. Consequently, the project decided to switch to a water–glycol solution.

This transition did not require substantial retrofitting of the cooling infrastructure: cooling plates for electronics have been already designed having alternative medium in mind. The cooling test rig; however, required replacement of the flowmeters calibrated for 50% water-glycol solution. Evaluation of the pilot cooling plant's performance under the new medium concluded feasibility of simple replacement of NOVEC 649 with water-glycol solution in the pipelines and the plant's secondary side [4]. Necessary work has been done to accomplish this task with the help of a contractor. First trial run with the new medium has been done in February, 2026 and confirmed that the cooling supply is capable of operating under new conditions.

The STS mainframe was assembled in the STS laboratory. The assembly procedure followed the defined integration sequence: the bottom carbon-fibre (CF) sandwich plate was positioned on the dedicated assembly table, followed by installation of the glass-fibre support skeleton. Subsequently, the top CF sandwich structure and the rear wall were mounted, completing the mechanical envelope of the detector frame.

After successful assembly, the mainframe was transferred to its designated parking position in the STS laboratory. In its current configuration, it is fully prepared to receive the Half Units once they become available from the production chain.

A final mechanical iteration with the carbon-fibre conical beam pipe was carried out to validate the interface geometry and clearances. The beam pipe underwent mechanical inspection and successfully passed vacuum tests, confirming its structural integrity and leak tightness under operational conditions.

With the completion of these activities, all major mechanical elements of the STS support structure are in place and validated. The system is therefore ready for final integration, pending delivery and qualification of the Half Units.

Outlook 2026

In 2026, the CBM-STS project will transition from large-scale preparation to full production and system integration. Series production of STS modules will be finalised, while ladder assembly will continue at increased throughput enabled by the second assembly line, aiming at completion of the full set of ladders. Parallel ladder qualification and calibration will proceed to maintain readiness for detector integration [5].

Half Unit production is expected to start following the successful prototyping phase, supported by the now commissioned assembly and test infrastructure. The first fully equipped Half Units will undergo mechanical, electrical, and thermal validation.

On the infrastructure side, the laboratory installations and cooling systems will be consolidated for routine operation. Integration of Half Units into the STS mainframe is expected to begin toward the end of the year.

In parallel, progress is anticipated on CBM cave infrastructure and magnet production, including preparation for the Factory Acceptance Test of the superconducting magnet in Fall 2026.

Selected publications of 2025

[1] S. Mehta, "Investigation of thermal and structural integrity of modules and ladders of Silicon Tracking System of the CBM experiment," PhD thesis, U. Tubingen, 2025. doi: 10.15496/publikation-104689.

[2] M. Teklishyn, "Detectors and electronics for the CBM experiment at FAIR," J. Subatomic Part. Cosmol., vol. 4, p. 100250, 2025, doi: 10.1016/j.jspc.2025.100250.

[3] A. Agarwal et al., "Performance of the prototype silicon tracking system of the CBM experiment tested with heavy-ion beams at SIS18," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 1082, p. 171059, 2026, doi: 10.1016/j.nima.2025.171059.

[4] K. Agarwal, "Thermal Management of the Silicon Tracking System of the CBM Experiment at FAIR," PhD thesis, U. Tubingen, Eberhard Karls Universität Tübingen (DE), 2025. doi: 10.15496/publikation-102494.

[5] A. Rodríguez Rodríguez, "Advancements in the Silicon Tracking System of the CBM experiment: module series production, testing, and operational insights," JINST, vol. 20, no. 3, p. C03020, 2025, doi: 10.1088/1748-0221/20/03/C03020.

3.4 HADES

Head: Prof. Dr. Joachim Stroth (Goethe University Frankfurt & GSI)

Authors: Tetyana Galatyuk, Jerzy Pietraszko, Anar Rustamov, Joachim Stroth, Christian Wendisch

Introduction

In 2025, the HADES collaboration successfully concluded the Au+Au beam energy scan which had been interrupted in 2024 with the failure of the superconducting magnet's cryogenic system. After a successful repair of the system using used heat exchangers running for 10 days between April and May was sufficient to collect the anticipated statistics, thanks to an excellent performance of the detector and the stable operation of the Spill Optimisation System [1]. The HADES detector is now being reconfigured to prepare for measurements with pion beam. The combination of secondary pion beam with the large Acceptance Di-Electron Spectrometer is a world-wide unique facility to address open questions in baryon structure and in-medium modification of vector mesons in cold nuclear matter. The planned program with pion beam is laid out in the document π-QCD accessible via the HADES home page.

Completion of the Au+Au Beam Energy Scan

Smooth data taking

HADES experienced a smooth running with gold beam in spring 2025. Short accelerator setup times, and excellent duty factor of the extracted beam reaching beyond 90% beam on target, and a good micro spill structure with moderate beam intensity fluctuations in the microseconds time range enabled smooth data taking with stored-event rates reaching 15 kHz in the flat top. This is record for HADES when running heavy-ions and is the result of a slow extraction operated by the SOS and a reduced dead-time of the HADES readout thanks to the new drift chamber readout electronics (MDC FEE) installed on the first two tracking plans. After the very positive start-up of the experiment in 2024 where a comparable performance had been observed, yet without new MDC FEE, this observation demonstrates the high reliability of the new extraction system. The high performance of the experiment was supported also by a reduced failure rate of the DAQ system and a very stable operation of the drift chambers only very rarely experiencing beam-intensity spikes.

To control the slow extraction, HADES provided a low-level trigger signal to the system generated from coincident particle hits the HADES' time-of-flight and multiplicity detectors. A coincidence with the signal from the in-beam T0 detector, the configuration used to trigger the data acquisition of the experiment, was avoided to keep sensitivity to expected efficiency degradation of the T0 detector due to the high dose imposed by the focused gold beam on the CV diamond-based sensors. The collected luminosity is shown in Figure 32. Peak mean event rates reaching 15 kHz blame been achieved e.g., on May 1st running gold beam of 800 AMeV. These values are about a factor two larger than assumed in the proposal.

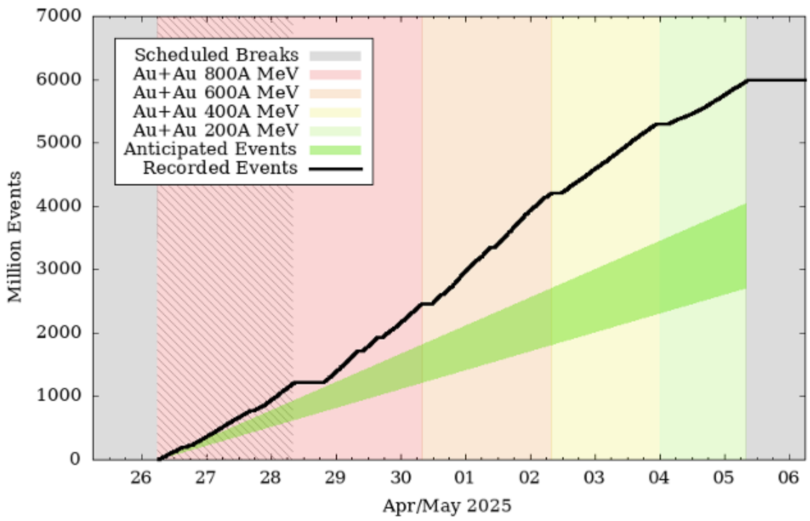

Figure 32: Events accumulated during nine days of gold beam in April/May 2025 (black line). Plateaus are mainly due to beam sharing with parasitic users, energy tuning, and shorter breaks. The coloured background shown indicate the four runs for the various beam energy settings as reported in the inset. The corridor indicated as green wedge reflects the anticipated performance assumed in the proposal (lower boundary) and the speculated gain factor due to the upgrade of the DAQ system (new MDC FEE and other measures) (upper boundary).

Experiences with the new MDC FEE

For the upgrade of the HADES tracking detectors, a total of 372 motherboards will be exchanged with the new version featuring the PASTTREC analog-amplifier-discriminator chip and digitization on FPGA. In contrast to the old FEE, the new boards have multisite capability which will improve the track reconstruction in an environment with chance-coincident hits due to delta electron emission from non-interacting beam ions passing the target. Another improvement results from the much faster clock cycle of the readout and a consequently reduced dead time. Between the runs in 2024 and 2025 the inner two tracking planes were already upgraded by replacing a total of 180 motherboards on each six chambers of MDC-I and MDC-II. The positive effect of a faster readout can clearly be seen in Figure 33. It compares "screen shots" of the online DAQ monitoring visualizing the dead times of the various detector systems. While MDC-I and MDC-II were dominating the dead time in 2024, they now lie in the range of the other readout systems. After completion of the exchange for the outer chamber MDC-III and MDC-IV, it is conceivable that the total dead time of the HADES readout will reduce by a factor of three. For runs with proton or pion beam with low multiplicity in the final state, event rates of up to 100 kHz are in reach. Event rates during the flat top in the Au runs in 2024 and 2025 were 8 and 13 kHz, respectively. The precision in the time measurement has not changed while the peaking time of the PASTTREC is slightly longer than for the ASD-8, the analogue chip used in the old readout electronic.

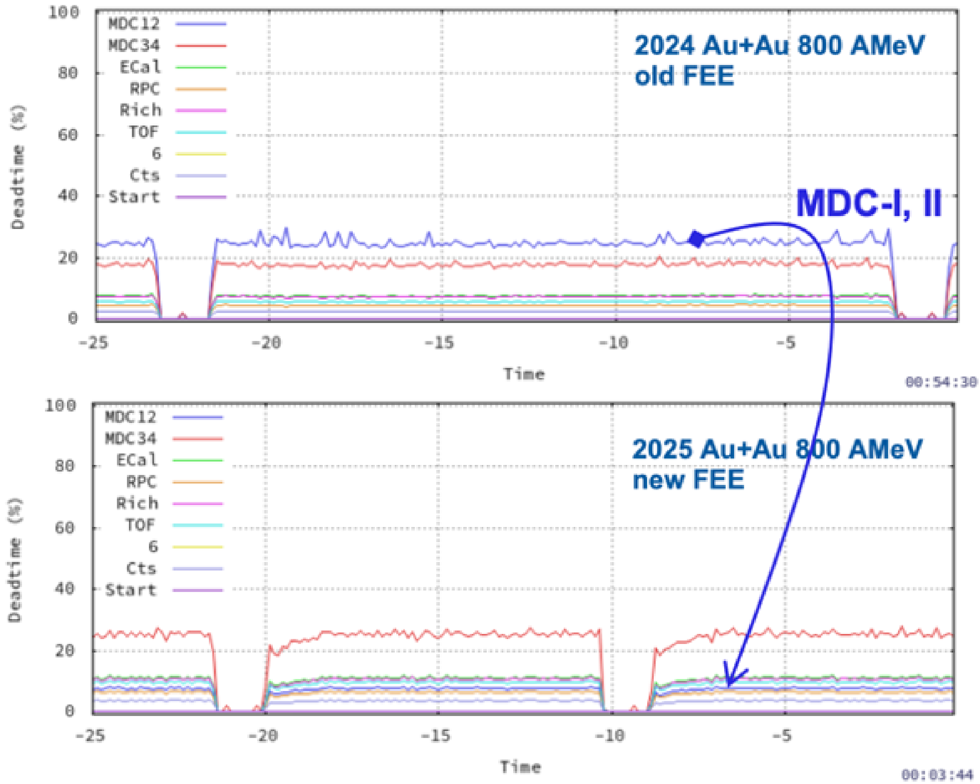

Figure 33: Instant dead times of the various readout systems as a function of time (in seconds) of HADES detectors in the beam times 2024 and 2025. The readout systems for the inner (MDC12) and outer tracking planes (MDC34) a recorded separately. The other detector systems are also shown (see legend). The extraction time in 2024 was a factor two longer than in 2025.

First test with double sided LGAD strip detectors

Low-gain avalanche diode have received a lot of attention in recent years as technology for large area, high granular timing detectors in particle physics application. The HADES department (Jerzy Pietraszko), together with TU Darmstadt and the Detector Laboratory at GSI has launched a project to develop this technology for in-beam detectors with low-ionizing beams like pions and protons [2]. A spin-off application is pursued in collaboration with Med-Austron and the Marietta Blau Institute in Vienna. The innovative use case proposed is dose monitoring in irradiation treatment using time-of-flight technology instead of calorimetry [3].

The main challenge is to achieve high precision in timing, excellent position resolution, high rate capability and high resilience against radiation damage. Since granularity is a design parameter of minor importance for that application, LGAD sensors have been developed with single-sided strip read-out (two-times 48 strips with 387 µm pitch) and successfully used in the 2022 beam time (S518) with proton beam up to beam intensities of 100 MHz. A timing precision of 80 ns has been observed with test beams. In production runs similar values are reached after careful time-walk corrections, based on a time-over-threshold signal derived from the read-out electronics and encoding the integral charge of the individual signals, and for various levels of radiation damage. In that measurement the beam spot on the T0 detector amounted to about 5 mm^2 (95% of the intensity).

In the most damaged region, the sensor received an integral non-ionizing dose of 10^{14} n_{eq}/cm^2. In that beam time, two such sensors had been placed close behind each other to provide two-dimensional position measurements.

As a next step, R&D was started to evaluate sensors with two-side strip patterning. The goal is to further reduce material budget for the in-beam measurement. To achieve that, sensor material from FBK Trento has been used. Single-sided LGAD devices with usual segmentation on the low-voltage side were post-processed on the gold-plated back side (high voltage side) to achieve segmentation down into the bulk material. This work was carried out by Hahn-Schickard-Gesellschaft für angewandte Forschung e.V., Villingen-Schwenningen, Germany. For that, trenches were introduced with a depth of about 120 µm (2/3 of the sensor thickness) such that strips of remaining bulk with a pitch of 100 µm were formed. For operation, voltage is applied to each strip through a load resistor while the front-end electronics is AC coupled to the individual strips (see Figure 34). For test purposes, the strips on both sides had been aligned (zero stereo angle). The prototype sensor was tested in using a ^{90}Sr source. A perfect linear correlation was found between the position of a seed strip on the front side and the strip fired on the back-side implying a near to 100% signal efficiency of the back side strips. Energy resolution is also demonstrated by correlating the time-above-threshold from hits read out on the front and back-side strips. These are first impression from a novel device based on LGAD technology with a great perspective for various application in ion-beam experiments, and beyond.

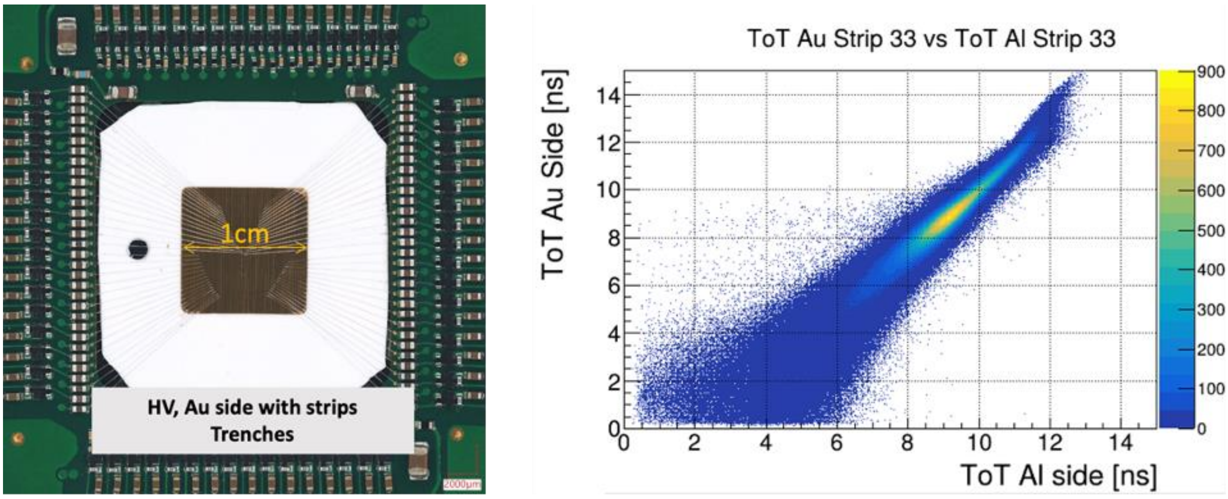

Figure 34: (left panel) Photograph of the back-side of the LGAD double-sided strip after integration on the readout board. Note the bonding to the active region of the sensor to accommodate connection for all stripes to the four-sided readout structure on the FEE PCB. (right panel) Correlated time-above-threshold measured for electron from a strontium source.

Highlight from data analysis

Towards the measurement of the thermal conductivity of QCD matter

The in-medium vector spectral function encodes the electric conductivity of a medium in its low-mass, long-wavelength limit. Within the Vector Dominance Model (VDM), for a hadronic system the in-medium spectral function is well described by the in-medium ρ propagator, accessible in experiment after proper subtraction of non-thermal contributions to the integral invariant mass distribution of lepton pairs (e^+e^- or $\mu^+\mu-$), see Figure 35. The experiment challenge, besides the generally small branching ratios for electromagnetic decays of vector mesons, is to achieve high acceptance for pairs in the relevant phase-space regime and to precisely determine the contribution from π^0 Dalitz decays. The latter over-shine possible thermal contributions substantially. On the other hand, the measurement with HADES at SIS18 beam energies benefits from the fact, that mesons are not abundantly produced. As can be seen from the Cocktail in Figure 35, the expected contribution from η Dalitz decays is substantially below the conjectured contribution of in-medium ρ decay.

To gain sensitivity in the low-mass region towards the photon point, HADES conducted data collection with the magnetic field reduced to 15% of the maximum field value. This setting was used for a few days during the silver run (S477) and allowed electron and positron candidates to be reconstructed down to momenta of 20 MeV/c. Careful simulation studies were required to assess the response of the HADES tracking system for these types of tracks as significant energy loss occurs along the trajectory of the leptons, particularly when traversing the RICH mirror and radiator shell. While the analysis is still ongoing, the comparison of the integral invariant mass spectrum to the contribution of π^0 Dalitz decays appears to be promising as the data indicate a significant access in the mass region below 140 MeV/c^2. A detailed evaluation of the systematic uncertainties and the subtraction procedure will be conducted to determine the access radiation in that invariant mass regime. Moreover, depending on the statistical significance, the lepton pairs will further be restricted to low momentum (wavelength).

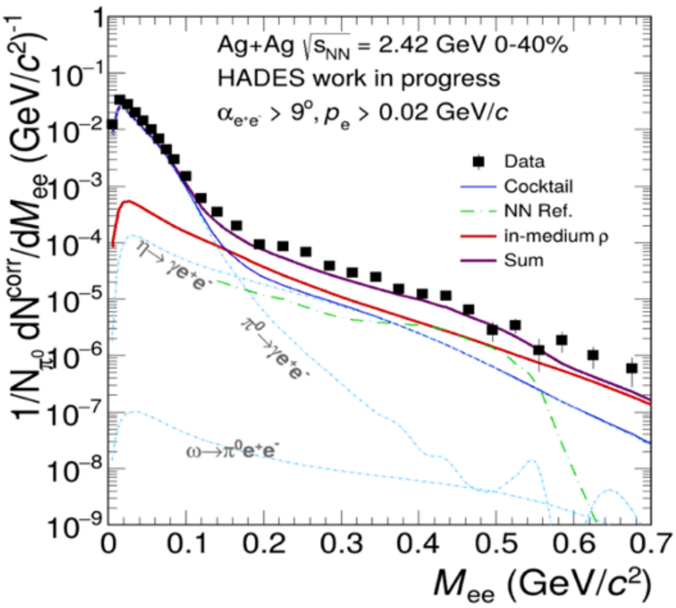

Figure 35: Dilepton (e^+e^-) invariant mass distribution for 40% most central silver-silver collisions at maximum SIS18 beam energy. Data was taken with a significantly reduced magnetic field setting to enhance acceptance for low-momentum electrons/positrons. The data is compared to a simulated spectrum (black line) including contributions from meson decays after freeze-out (cocktail), pre-equilibrium collisions (NN Ref.), and thermal contributions (in-medium ρ). Lepton momentum down to 20 MeV/c were accepted for pairing.

Higher-moments of deuteron event-by-event number fluctuations in Ag+Ag

The progress in identifying and mitigating instrumental as well as conceptional drawbacks in extract relevant dynamical fluctuations from measured event-by-event proton multiplicity distributions is impressive. In view of that progress the high-statistics data obtained in the 2019 Ag+Ag run at the beam energies of 1.56 GeV/u and 1.23 GeV/u are currently being reanalysed. The analysis steps now include a probabilistic particle identification (Fuzzy Logic PID) [4] to account for incomplete selectivity and finite purity. In a next step, extracted moments of the raw distributions are corrected for detector inefficiency including those caused by dead areas of the detection system otherwise contributing to the selected phase space region (aka acceptance). A strategy acting directly on the obtained moments of the raw distributions is the so-called Moment Expansion Method

HADES distribution for small regions of rapidity and transverse momentum. Applying the so-called Identity Method, moments of the event-by-event particle distributions can be derived applying fractional particle identities based on the fitted model functions [4]. Figure 36 shows the fitted mass distribution for a selected p_t-y bin and the resulting proton multiplicity distribution, which is continuous given the fractional probabilities assigned to reconstructed tracks. Further corrections to be applied are for the finite reconstruction efficiency and for fluctuations of the interaction volume in a given centrality class. Marvin Nabroth (HGS-HIRe / Goethe University Frankfurt) applied various methods in his ongoing studies and presented preliminary results in a parallel talk at Quark Matter 2025.

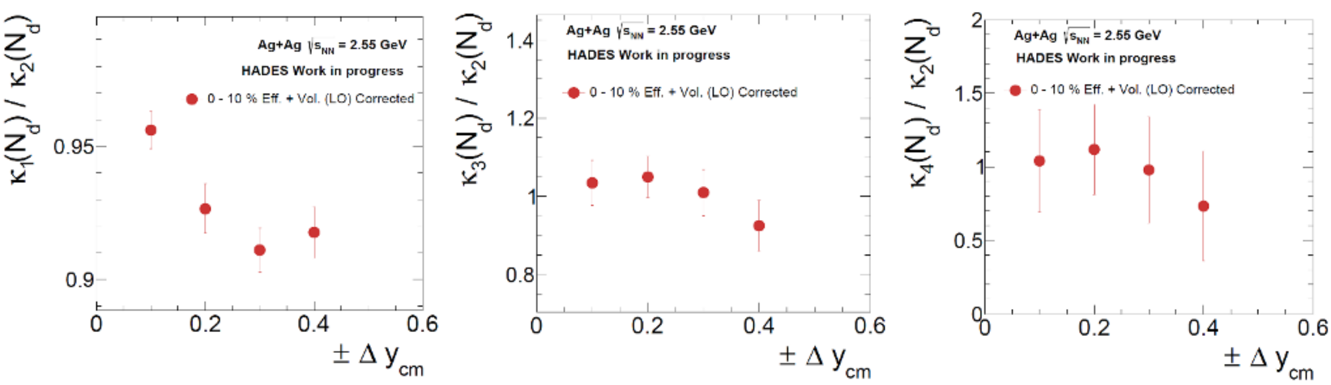

Figure 36: Deuteron cumulant ratios extracted from e-b-e multiplicity distributions obtained from the 10 % most central Ag+Ag collisions at maximum SIS 18 beam energy (S511). From left to right the inverse scaled variance, skewness ($s\sigma$) and kurtosis ($k\sigma^2$) are shown. The abscissa depicts the rapidity gap used to accept deuteron for multiplicity evaluation.

Outlook 2026

With the successful conclusion of the Au+Au beam energy scan in April/March 2025, the HADES collaboration has collected all data anticipated for the heavy-ion program at SIS18. The focus is now shifted to pion beam experiments proposed in "π-QCD Proposal for Experiments at the GSI Pion Beam Facility". The detector system is currently prepared for runs addressing exclusive channels by exchanging the Forward Wall with the Forward Straw Tracker System (fSTS) and the Forward RPC (fRPC). Moreover, the detector simulation package based on e-b-e delta electron treatment and with a refined embedding algorithm is ready for production. A large number of results from the S477 (Ag+Ag) beam time will now be efficiency corrected based on the new package and will be published soon. Likewise, many results from the S518 (p+p) run in 2022 are also close to be finalised.

Selected publications of 2025

[1] P. Niedermayer and R. Singh, "Excitation signal optimization for minimizing fluctuations in knock out slow extraction," Sci. Rep., vol. 14, no. 1, p. 10310, 2024, doi: 10.1038/s41598-024-60966-y.

[2] W. Krüger et al., "LGAD technology for HADES, accelerator and medical applications," Nucl. Instrum. Meth. A, vol. 1039, p. 167046, 2022, doi: 10.1016/j.nima.2022.167046.

[3] F. Ulrich-Pur et al., "First experimental time-of-flight-based proton radiography using low gain avalanche diodes," Phys. Med. Biol., vol. 69, no. 7, p. 075031, 2024, doi: 10.1088/1361-6560/ad3326.

[4] A. Rustamov, "Fuzzy logic for reconstructing arbitrary moments of multiplicity distributions," Phys. Rev. C, vol. 110, no. 6, p. 064910, 2024, doi: 10.1103/PhysRevC.110.064910.

4. Research of the NUSTAR Departments

Coordination: Christoph Scheidenberger (GSI Darmstadt, JLU Gießen, HFHF Gießen)

4.1 Executive summary

Authors: Helena Albers, Thomas Aumann, Michael Block, Timo Dickel, Christoph E. Düllmann, Magdalena Górska, Alexander Herlert, Christoph Scheidenberger

Introduction & Overview

NUSTAR continues to play a central role in advancing the scientific program at FAIR and GSI. Its research spans nuclear structure far from stability, nuclear astrophysics, reaction studies with rare isotopes, and the physics and chemistry of superheavy elements. A particular focus lies on exotic nuclei and their role in the synthesis of elements in the universe, as well as on pushing the limits of nuclear existence. The activities benefit from a uniquely strong and well-integrated international community, combining experimental, theoretical, and technical expertise. This collaborative strength enables NUSTAR to address some of the most fundamental open questions in nuclear physics and astrophysics in an ongoing experiment program, while simultaneously preparing for the transition to FAIR operation. The NUSTAR departments and research groups, primarily located at GSI and the HI Mainz, are embedded in this international network and central for many collaborative tasks.

The activities of NUSTAR are firmly integrated within the FAIR framework. Construction of the FAIR facility progresses, and the collaboration already exploits the existing GSI accelerators in the FAIR Phase-0 program; some detectors and instruments built for FAIR are already being used in Phase-0. At the same time, extensive preparations are ongoing to ensure a smooth transition to the future FAIR experimental environment, in particular to the Super-FRS and its associated experimental branches.

Central Scientific Objectives

The scientific program of NUSTAR is driven by a set of overarching questions that connect nuclear structure, reactions, and astrophysics. One key objective is the understanding of the third r-process abundance peak through systematic studies of nuclei around the neutron shell closure at N = 126. These investigations require precise measurements of nuclear masses, lifetimes, decay properties, and electromagnetic response, providing essential input for astrophysical models of heavy-element nucleosynthesis. The exploration of the limits of nuclear stability—both at the proton and neutron driplines, as well as at the upper end of the nuclear chart through superheavy element research—constitutes a central objective.

Another major goal is to probe the equation of state of asymmetric nuclear matter. This is achieved through measurements of observables such as dipole polarizability and neutron-skin thicknesses in neutron-rich nuclei. These quantities are directly linked to fundamental properties of nuclear matter and have implications for the physics of neutron stars.

In addition, NUSTAR explores exotic nuclear systems, including hypernuclei and nuclei with extreme proton-to-neutron ratios. These studies provide insight into the underlying nuclear forces and the emergence of structure in systems far from stability. Together, these research directions form a coherent framework that connects microscopic nuclear properties with macroscopic phenomena in the universe.

Experimental Infrastructure & Programs

NUSTAR relies on a comprehensive set of experimental facilities and detector systems. Core instruments include SHIP/SHIPTRAP and TASCA for superheavy element research, the Fragment Separator (FRS) and its detector systems, as well as the R3B and the HISPEC-DESPEC setups for spectroscopy studies. Research at these systems forms the backbone of the current experimental program and they are being further developed for operation at FAIR.

The FAIR Phase-0 program, conducted at the existing UNILAC and SIS18 accelerators, continues to provide essential opportunities for high-impact experiments. It serves both as a platform for scientific discovery and as a testbed for new detector technologies, data acquisition systems, and analysis methods. These include improvements in efficiency, resolution, and sensitivity, as well as the validation of novel experimental techniques. Such developments are crucial for ensuring the performance required for future experiments at FAIR.

Progress & Technical Developments

Simultaneously, intensive efforts are ongoing to prepare for the science program for the FAIR Early Science and First Science staging steps. Significant progress has been achieved in the technical realization of NUSTAR experiments at FAIR: the preparation of the installation and integration of detector components in the new experimental areas has advanced considerably, supported by dedicated technical workshops and coordination efforts. These activities address key challenges such as detector alignment, beam diagnostics, and data acquisition integration.

Scientific Highlights 2025

The year 2025 was marked by several important scientific achievements across the NUSTAR collaboration. In the field of superheavy elements, the identification of two new neutron-poor superheavy nuclei, both published as “Editor’s choice” papers in Physical Review Letters, and one selected as one of only three papers from the year 2025 in Phys. Rev. Lett. in the field of nuclear physics represents a significant step forward in exploring the limits of nuclear existence and the structure of the heaviest systems. One work reports the discovery of 60-ns ^{252}Rf, which is the most short-lived known superheavy nucleus and could only be detected thanks to its more long-lived isomeric state, while the other reported the new isotope ^{257}Sg and the first observation of an isomeric state of similar nature in an Sg isotope.

A major highlight in nuclear reactions and structure studies was the publication of an R3B FAIR Phase-0 experiment in *Nature*, reporting on the discovery of a new “island of asymmetric fission.” This result provides novel insight into fission dynamics and challenges existing theoretical descriptions of the fission process. Further advances were reported from R3B experiments investigating nuclear structure of fluorine isotopes at the neutron dripline through exclusive reaction measurements, demonstrating the power of kinematically complete experiments with rare-isotope beams.

The HISPEC/DESPEC collaboration succeeded to investigate – for the first time – the lifetimes of intermediate states below isomeric levels, enabling exploration of the competition between valence configurations outside the closed core and virtual core excitations, thereby providing insight into the robustness of the ^{100}Sn shell closure. By moving from the two-proton-hole nucleus ^{98}Cd to ^{100}Cd, with the addition of two valence neutrons, an extra degree of freedom arising from proton–neutron interaction was experimentally introduced. A novel method to extract interaction positions on the DESPEC bPlast plastic detectors was developed for DESPEC experiments using a highly-segmented double-sided silicon strip detector (AIDA) with significantly improved position resolution.

At the Super-FRS Experimental Collaboration, a direct mass measurement of the neutron-deficient nucleus ^{93}Pd has provided valuable constraints on binding energies near the proton drip line, with implications for nucleosynthesis pathways, the nuclear structure of ^{94}Ag and its isomers. In close collaboration with the theory department recent high-precision mass measurements of neutron-rich tin isotopes provide key constraints on shell evolution far from stability and significant improvements of astrophysical r-process models.

New initiatives are also emerging, such as research activities within LASPEC, where newly appointed fellows aim to exploit the Super-FRS already in an early stage for high-precision laser spectroscopy of exotic nuclei. These efforts will enable detailed studies of nuclear ground-state properties and shape coexistence.

Another notable highlight from laser-spectroscopic investigations of exotic nuclei concerns the identification of fingerprints of “almond-shaped” (triaxial or reflection-asymmetric) nuclei. These studies open new perspectives on nuclear deformation and collective motion, revealing previously inaccessible aspects of nuclear structure.

Overall, substantial progress has also been achieved in nuclear structure and reaction studies, with a broad range of experiments contributing to a deeper understanding of exotic nuclei.

FAIR Phase-0 Significance

The FAIR Phase-0 program continues to be of outstanding importance for the NUSTAR collaboration. It provides a unique environment in which forefront scientific results can already be achieved while preparing for future FAIR operations.

Beyond its scientific output, Phase-0 plays a critical role in the development and validation of experimental techniques, detector systems, and data analysis methods. It also serves as an essential training ground for early-career researchers, ensuring the availability of highly skilled personnel for the upcoming FAIR program.

Collaboration & Events

The NUSTAR collaboration remains highly active and well-coordinated through a series of regular meetings and governance structures. The NUSTAR Council, via a Memorandum of Understanding framework, continues to guide the collaboration’s activities and strategic development. A new MoU for the operation phase of FAIR has been drafted and under discussion with the funding agencies.

The NUSTAR Annual Meeting 2025, which also marked the 25th anniversary of FAIR-GENCO, the GSI Exotic Nuclei Community, brought together a large number of participants to discuss scientific progress and future plans. The meeting included a memorial session honouring Gottfried Münzenberg, whose pioneering contributions to superheavy element research and in-flight separation have had a lasting impact on the field.

In addition, the *NUSTAR Week 2025*, held in Prague (CZ) (see Figure 37), provided an important forum for detailed discussions on the transition to FAIR operations and the organization of Early Science activities. Further international engagement was demonstrated through events such as the Theme Meeting on FAIR Science in India.

Technical coordination and the Phase-0 program were also key topics of discussion, reflecting the importance of aligning scientific goals with technical readiness.

Figure 37: Participants of the *NUSTAR Week 2025* in September in Prague.

Strategic Activities

A major milestone in 2025 was the successful scientific centre evaluation in preparation for the POF V period within the Helmholtz program, which received an excellent assessment. This outcome highlights the strong scientific performance and strategic relevance of the NUSTAR activities.

At the same time, preparations for the next Program-Oriented Funding (POF) period V (2028–2034) are ongoing. These efforts focus on defining priorities, developing a technical roadmap, and ensuring the long-term sustainability of the research program in the FAIR era. The proposal for the scientific program involving GSI/FAIR within the research area Cosmic Matter in the Laboratory has been submitted. A strategic evaluation of the Matter and Universe program is scheduled for May 2026.

Future Challenges & Perspectives

Looking ahead, the primary challenge for the NUSTAR collaboration is the successful commissioning and operation of experiments at FAIR, in particular at the high-energy branch of the Super-FRS. This will open new frontiers in the study of exotic nuclei.

Research on the physics and chemistry of superheavy elements will continue to explore the "island of stability," aiming to map its extent and understand the underlying nuclear shell structure, atomic as well as chemical properties. These studies will benefit from improved beam intensities and advanced detection techniques.

In parallel, new experimental opportunities will arise with the HELIAC accelerator, which will enable high-precision studies of heavy and superheavy nuclei. The combination of these developments ensures that NUSTAR is well positioned to remain at the forefront of nuclear science in the FAIR era.

4.2 SFRS/FRS

Coordination: Christoph Scheidenberger (GSI Darmstadt, JLU Gießen, HFHF Gießen)

Authors: Daler Amanbayev, Timo Dickel, Emma Haettner, Christine Hornung, Nicolas Hubbard, Daria Kostyleva, Rinku Kumar Prajapat, Ivan Mukha, Wolfgang R. Plaß, Sivaji Purushothaman, Elena Rocco, Takehiko Saito, Christoph Scheidenberger, Yoshiki Tanaka, Jianwei Zhao

Introduction

The NUSTAR SFRS/FRS Experiments department plays a key role within the NUSTAR Collaboration and is a core contributor to the Super-FRS Experiment Collaboration. Its members carry out pilot experiments at the FRS at GSI as well as at external facilities, while simultaneously advancing instrumentation and preparing future experimental campaigns at the Super-FRS at FAIR. The scientific program is cantered on the investigation of exotic nuclei using a broad range of experimental techniques, extending in scope to applications such as the use of radioactive beams in biomedicine.

The department operates the FRS as an international user facility for experiments with relativistic radioactive beams and continuously develops and upgrades its capabilities. Through these efforts, it supports experimental activities with exotic nuclei at SIS-18 within both the NUSTAR and APPA collaborations; these aspects are outlined in the first section. The second section focuses on how the FRS, together with its associated detector systems and in close coordination with the Super-FRS Experiment Collaboration, is utilised for the department's own research program, including complementary work at UNILAC and other laboratories. The third section highlights ongoing developments aimed at preparing the experiment program at FAIR.

Experiments with exotic nuclei at SIS18

The main instrument of the department NUSTAR SFRS/FRS-Experiments is the fragment separator FRS, a high-resolution magnetic separator and spectrometer. It has a triple capability as it is used (i) for in-flight separation (i.e.: production, separation and identification of exotic nuclei), (ii) as high-resolution momentum spectrometer for experiments with relativistic beams from p to U, and finally (iii) the FRS serves as development and test platform for next-generation NUSTAR experiments at the Super-FRS. In 2025, the NUSTAR Collaboration has taken advantage of the FAIR Phase-0 and performed a number of experiments using the FRS, which are listed in Table 2.

The **support of experiment groups** ranges from the development of experimental proposals to the publication of results; the requirements vary depending on the specific needs of an experiment and the individual experience of a group; it includes participation in the experiment conceptual design, simulations, technical implementation (mechanical setup, installation of experiment equipment, preparation of specific features of electronics, trigger, data acquisition and online analysis of the individual experiment, safety-related aspects), execution (the so-called "beamtime"), documentation and post-processing (book-keeping, data management, calibrations, data storage) and finally data analysis. The Horizon EU Programme of the European Commission supports many of the user group projects listed in Table 2 with the EURO-LABS Transnational Access to GSI activity, which is managed by the members of the FRS/Super-FRS Experiments department.

The **upgrading of the scientific-technical infrastructure** continued in 2025, with a focus on reliability, maintainability, and compliance with FAIR standards. At the first focal plane, the KUKA manipulator for equipment handling in the activated environment, for which spare parts are no longer readily available, was replaced by a new portal crane. This ensures reliable operation and facilitates routine maintenance and handling of beam insertions (like detectors, slits, degraders) installed at this location. In the target area a bridge over the separator was installed, providing improved and faster access to different experiment zones. A major effort was the replacement of the more than 35-year-old stepper motor control system with the new COSYLAB controllers. As the FAIR standard solution, these controllers offer enhanced reliability, long-term compatibility with future FAIR infrastructure developments and several new features, which increase reliable and fast beam manipulation. The modularization of experiment equipment was continued at the main focal planes (midplane and final focal plane) of the FRS. This concept was originally developed for the FAIR Phase-0 experiment series, where many different experiments with individual setups are carried out within a short period of beam time, and it has been gradually implemented over the years.

On the **hardware** side, the installation of new particle-identification detectors has enabled advanced analyser–spectrometer experiments. In late 2024, a novel SCI-TOF system was installed at the first focal plane. The system features a ladder incorporating four independent scintillator detectors with two-sided photomultiplier-tube readout, enabling reliable operation even during high-rate/high-dose measurements. It provides simultaneous position and timing measurements (under quite demanding conditions) and time-of-flight (TOF) measurements over the relatively short distance between the first and the central focal plane. To achieve full particle identification, velocity and position measurements are complemented by two new multiple sampling ionization chambers (Travelling MUSICs) installed at the central focal plane, yielding atomic number (Z) identification. The enhanced capabilities of the combined system were successfully demonstrated in January 2025 as part of the experiment G-22-0160 titled "FRS developments for APPA and NUSTAR experiments: Performance improvements and R&D work with heavy-ion beams". Overall, the addition of the SCI-TOF system combined with the Travelling MUSIC detectors represents a significant enhancement of the FRS capabilities. The upgraded detection system was successfully used for several experiments during the 2025 beam times: several key experiments took advantage of it, namely "Study of a nuclear sandbank at the proton-unbound bromine isotopes" (G-22-00115), "Testing diamond detectors for development of an active target" (G-22-0092) and "Neutron skin measurement of ^{132}Sn and ^{144}Xe" (G-22-00027), highlighting the new capabilities, which are now routinely available for user experiments. Figure 38 shows photographs of the new detectors and a particle-identification plot for fission fragments as obtained with the second stage of the first half of the FRS.

Experimental Program 2025					
Experiment Number	**Experiment Title**	**Spokesperson**	**Shifts**	**Dates**	**Beam**
G22-0160	FRS developments for APPA and NUSTAR experiments	C. Scheidenberger	12	05.02-06.02	^{107}Ag
G22-0056	Nuclear symmetries and structure studies via mass measurements at the N=Z line from Ge to Rh	W. Plaß	18	07.02-12.02	^{107}Ag
G24-0302	Test of the DESPEC Implantation Stack Detectors	H. Albers	9	22.02-25.02	^{107}Ag
G22-0115	Study of a nuclear sandbank at the proton unbound bromine isotopes	M. Pfützner	12	28.02-03.03	^{78}Kr
G22-0150	Mass measurements at N≈126 for understanding the 3rd r-process abundance peak	C. Scheidenberger	21	31.03-06.04	^{208}Pb
G22-0103	Test of the beam tracking and identification for HISPEC-10	J. Vesic	12	08.05-12.05	^{56}Fe
G22-0092	Testing diamond detectors for development of an active target	K. Wimmer	6	13.05-14.05	^{56}Fe
BIO	BARB	M. Durante	9	20.05-22.05	^{12}C
G22-0111	Towards limits of nuclear structure by using a ^{9}C beam	V. Chudoba	12	23.05-26.05	^{12}C
G24-0249	Unveiling the structure of neutron-rich Z=9 isotopes: the case of ^{25}F	V. Panin	24	04.06-11.06	^{40}Ar
G22-0027	Neutron skin measurement of ^{132}Sn and ^{144}Xe	R. Kanungo	9	17.06-21.06	^{238}U
G22-0182	Fission isomer studies with the FRS	J. Zhao	6	28.06-29.06	^{238}U
G22-0143	TEST of DESPEC Fibre IMPlanter (FIMP)	M. Vencelj	9	04.06-06.06	238-U
Total	**13 Experiments**		**171 shifts**		

Table 2: Experiments with radioactive beams performed in year 2025 in a collaborative effort by the FRS/Super-FRS Experiments department, the NUSTAR Beam Team, and the individual sub-collaborations of NUSTAR and APPA, respectively.

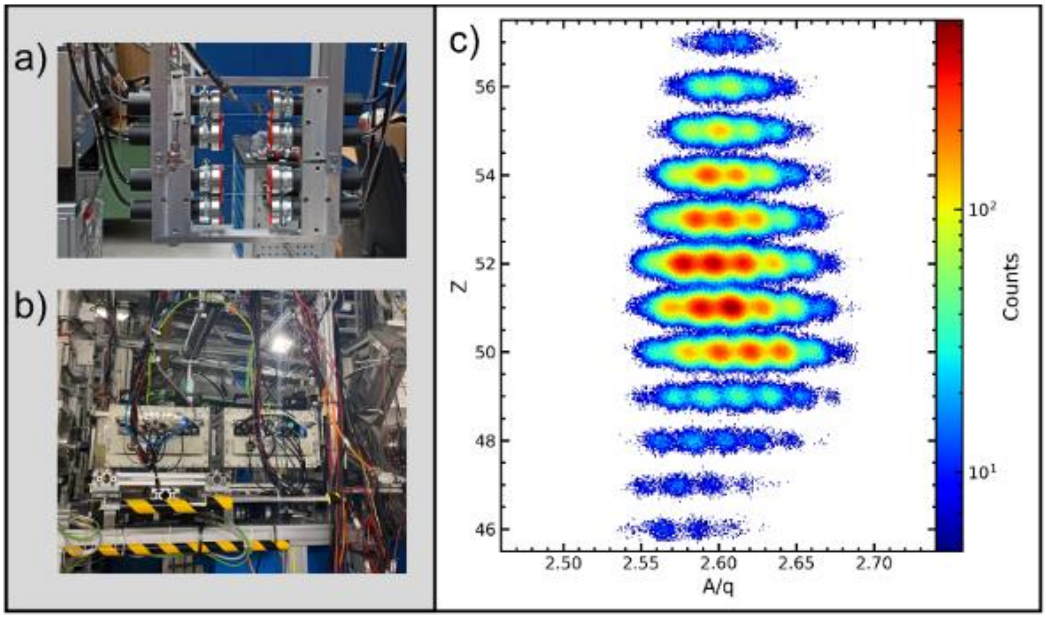

Figure 38: a) New scintillator ladder featuring 4 separate scintillator systems with 2-sided PMT readout used at F1. b) Installation of two new multiple sampling ionization chambers (Travelling MUSICs) at F2 c) Identification of fission fragments in the region of ^{132}Sn using the new SCI-TOF system at the F1 focal plane. Together with the position and Z measurements at F2, event-by-event particle identification of the exotic nuclei of interest is achieved. Example is from “Neutron skin measurement of ^{132}Sn and ^{144}Xe” (G-22-00027).

A new current grid (for beam-profile measurements of intense slow-extracted and fast-extracted beams) has been prepared and is almost ready for installation at the mid-focal plane of the FRS. This upgraded version incorporates enhanced testing capabilities at the wire level, allowing improved functionality checks prior to a beam time. As a second beam detector of this type at this focal plane, it will enable measurement of the beam angle in addition to beam position. This development represents an important improvement for all FRS experiments, and is particularly relevant for FRS–ESR experiments, as the additional information will provide rapid feedback on beam alignment during the setup phase and thereby reduce overall setup time.

On the **software** side, a key development is the FRS remote control from the FAIR Control Centre FCC. In preparation of this, the experiments performed in 2025 used a new monitoring solution: the "**FRS Virtual Messhuette**". Hosted on the web portal *lxfrs.gsi.de*, this tool replicates monitoring functionalities of the physical FRS Messhuette (the counting room in the shack), enabling remote access for experimentalists anywhere via the Internet. The "FRS Virtual Messhuette" integrates data from the accelerator control system, the FRS data acquisition system, and dedicated hardware such as live scalers read out via serial port, offering a comprehensive, real-time overview of FRS and accelerator operations; a typical screenshot is displayed in Figure 39. This enables remote monitoring and troubleshooting by experiment participants without the need to be physically present. In addition, a connected Grafana database ensures long-term logging of key parameters, with a data retention period exceeding ten years. The "FRS Vitual Messhuette" has been well-received by users and is now firmly established as an important monitoring tool for FRS experiment participants.

Figure 39: The upper part shows the visual representation of the "Virtual Messhuette", providing a clear overview of the separator's status, the lower part shows the FRS drive status, with nomenclature and stepper motor position lookups provided.

In this context, the "trigger box" of the FRS data acquisition system was replaced with a software solution (using the GSI VULOM module and Python), which replicates the hardware functionality exactly, while enabling remote control, as depicted in Figure 40. In addition, the software allows the selected options (including downscale, and per-trigger dead time) to be recorded into the data, improving operational reliability, reproducibility and analysis of the data.

For improved beam analysis, a new standalone data-acquisition system was introduced to monitor the time-structure of the beam from the SIS18, by using a VULOM-II module by the GSI EE department as a triggerless TDC: the full structure of the spill can be analysed in real-time, both the large scale "macro" and individual "micro" spill structure are monitored, and made available on the FRS Virtual Messhütte and to the HKR as a monitor.

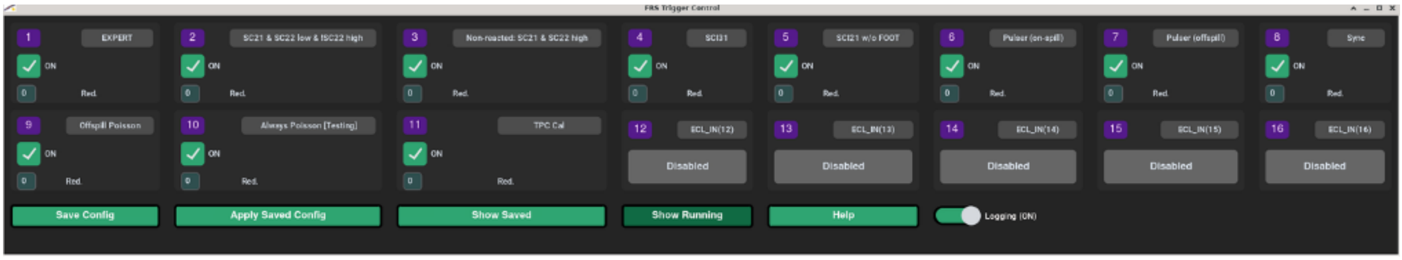

Figure 40: Visual representation of the software-based trigger box.

The SFRS/FRS Experiments department supports the experiment groups also with a public **data repository** that includes logbooks, simulation outputs, and processed experimental datasets. These per-experiment files are stored on a large, backed-up server operated by GSI and made available on the Internet through an Apache Web Server. Researchers access this content including the FRS Data Server interface available at *lxfrs.gsi.de*, which provides intuitive browser-based navigation of experiments, logbooks, and shared files via a web portal at https://lxfrs.gsi.de. Access control is enforced using the **EURO-LABS** AAI. Authentication is handled via the OpenID Connect protocol, with INDIGO IAM verifying the user's institutional credentials. Once authenticated, fine-grained authorization is enforced using experiment-specific sub-groups defined within the IAM. In addition, the same AAI integration governs access to a Grafana (an open-source visualization and analytics software to be found on https://github.com/grafana/grafana) instance that provides live monitoring of FRS detectors. This unified identity and access model ensures that both data sharing and operational monitoring are conducted under a coherent, secure, and federated framework.

To **enable experiments** with relativistic radioactive beams at the forefront of contemporary science, highly specialised teams with substantial expertise are required. Developing and maintaining such expertise demands continuous **training** as well as the regular integration of young researchers. Education and knowledge transfer therefore represent key components of a sustainable experimental program. The NUSTAR Beam Team has played a central role in preparing and conducting the experiments listed in Table 1 above. It brings together members from various NUSTAR sub-collaborations, including in-house groups such as Nuclear Spectroscopy and the Super-FRS Project group, as well as external partners from the Super-FRS Experiment Collaboration. Their strong commitment and the extensive collaborative support are gratefully acknowledged. A key objective is the training of early-career scientists and members of the Super-FRS Project group in preparation for future experiments at FAIR. These activities, largely coordinated by the FRS/Super-FRS Experiments department in close collaboration with the Super-FRS Experiment Collaboration, combine lectures, online modules, and practical hands-on training. A particularly important component was the beam-based training carried out under realistic conditions during experiment G-22-00160, which provided invaluable experience for upcoming experimental campaigns.

Scientific activities and results

Beyond the activities outlined above, the FRS/Super-FRS Experiments department pursues its own independent research program. Its scientific focus is closely aligned with the Super-FRS Experiment Collaboration and spans a broad range of topics in nuclear physics. These include emerging research directions such as exotic atoms, hypernuclei, and rare decay modes, as well as key questions related to nucleosynthesis and the equation of state of cold, asymmetric nuclear matter. In parallel, the program addresses fundamental challenges such as the discovery of new isotopes, precise measurements of ground-state properties (e.g., masses and radii), and studies of atomic collision processes.

Within the FAIR Phase-0 framework, the department is engaged in both online beam experiments and offline investigations, for instance at the FRS Ion Catcher. In addition, its members actively contribute to experimental campaigns at leading international facilities, including RIKEN, JYFL, CERN, and TRIUMF. In particular, the experiments at the TITAN-Experiment at TRIUMF (Vancouver, Canada), in which a mass spectrometer is used, which was designed, developed and implemented by members of the SFRS/FRS Experiment department, are yielding a rich harvest in recent years. Owing to space constraints, only a short overview of recent results can be given here, while further details are available in the publications referenced in the following text, all of which – with only one exception – appeared in year 2025.

Production cross-sections and yields of secondary beams

In 2025, analysis activities of production cross sections have focused on multiple datasets obtained in FAIR Phase-0 with ^{208}Pb, ^{170}Er, ^{238}U, and ^{100}Mo primary beams on beryllium targets, all of which are currently under detailed investigation. Several graduate students and young researchers are actively involved in these efforts and are developing strong expertise in measurement and analysis of production cross sections for exotic nuclei [1]. These activities require detailed and in-depth understanding of all aspects of a fragment separator: in-flight separation and particle identification, transmission, reactions, detectors, electronics and data acquisition are key competences for the future experimental program at the Super-FRS. In particular, the offline data analysis procedures have been refined, leading to significant improvements in mass resolution and an enhanced atomic number resolution. Several publications are in preparation.

Fission isomer studies

A particularly interesting aspect of nuclear structure is fission isomers or shape isomers, i.e., meta-stable excited nuclear states, which decay by spontaneous fission. Only scarce experimental information is available to date. The advances in experimental facilities and detection systems, however, allow one to revive the experimental activities on fission isomer studies. Recent advances in e.g., ^{235,236}U and ^{240,242}Am studied experimentally at the FRS/GSI and at IGISOL/Jyväskylä, and an overview of the program has been published [2]. In year 2025, the SFRS/FRS EC experiment G-22-00182 investigated the population of ^{236f}U via ^{238}U fragmentation and electro-magnetic dissociation reactions with an improved setup.

Matter and charge radii of dripline nuclei

In addition to production yields and cross-section measurements, reaction studies with radioactive ion beams provide insights into the properties and structure of nuclei near the driplines. Accurate charge-changing and total interaction cross-section measurements using the transmission technique allow the extraction of mean-square charge and matter radii [3][4][5][6]. The combination of matter and proton radii provides access to the geometrical structure of dripline nuclei, where phenomena such as halos, skins, and nucleon correlations prevail. Furthermore, the symmetry energy connects e.g., neutron skin thickness to the nuclear equation of state (EOS). The experiment "Neutron skin measurement of ^{132}Sn and ^{144}Xe" (G-22-00027) was carried out in year 2025, aiming at precise measurements of interaction and charge-changing cross sections for these nuclei. A ^{238}U beam at 1 GeV/u impinging on a lead target was used to produce the secondary ^{132}Sn beam. The experiment required unambiguous particle identification prior to the reaction targets that were located at the FRS central focal plane: the above-mentioned new particle identification system could provide event-by-event identification (see Figure 38). The data analysis has been started.

Nuclear cross sections for bio-medical applications of radioactive beams

The cooperation with the BARB Collaboration (see page 25) on biomedical applications of radioactive beams [7] continued in 2025. Members of the department contributed to the second tumour treatment experiment using a radioactive ^{11}C ion beam, which was produced and separated with the FRS and conducted in Cave M in May 2025. Treatment with radioactive beams benefits from image-guided therapy, as β^+-emitting isotopes can be visualised in vivo and in near real time using positron emission tomography (PET). The results from the first experiment, conducted in 2024, in which a mouse osteosarcoma was successfully treated, was published [8].

Proton radioactivity of dripline nuclei

The "excursions beyond the proton drip line" conducted in previous years continued in 2025, and the attention was devoted to the previously unobserved nuclide ^{20}Al, which is a 3-proton emitter [9]. Using the original method of in-flight decays and tracking flight paths of all decay products with silicon microstrip detectors, the $3p$-decay energy of the ^{20}Al ground state has been determined (through a detailed study of angular correlations of its decay products, ^{17}Ne$+p+p+p$) to be $1.93^{+0.12}_{-0.10}$ MeV. This value is significantly smaller than the predictions inferred from the isospin symmetry by using the known neutron separation energy of its mirror nucleus ^{20}N, which indicates a possible isospin symmetry breaking in the mirror nuclei ^{20}Al and ^{20}N. This observed isospin symmetry breaking is supported by the calculations of the continuum embedded theoretical frameworks, describing the observed ^{20}Al ground state as a $1p$ s-wave state with a spin-parity of 1^-, which differs from the spin-parity (2^-) of the ^{20}N ground state. The ^{20}Al ground state decays by sequential $1p-2p$ emission via the intermediate ground state of ^{19}Mg, which is the first observed case of "daughter" $2p$ radioactivity following $1p$ decay of the parent state [9].

Nuclear-structure investigations via high-precision mass measurements

As part of a campaign to investigate exotic nuclei at the N=Z-line with the FRS Ion Catcher [10] in FAIR Phase-0, the first direct mass measurement of ^{93}Pd, the one-proton-decay daughter of the (21+) isomer in ^{94}Ag, has been performed, reducing the mass uncertainty by an order of magnitude [11]. As a consequence, the excitation energies of the presumed parent states of the one-proton (1p) decay and two-proton (2p) decay in ^{94}Ag are found to differ from each other by ten standard deviations. This shows that there is an incompatibility in the previously reported decay scheme of the 1p and 2p branches and thus calls into question the observation of the two-proton decay in ^{94}Ag. State-of-the-art mean-field calculations have been performed, which confirm that, based on the reported decay information, the 2p emission cannot be fed from the same (21+) isomer as the 1p emission, but indicate that it could originate from a second high-spin state with strongly differing deformation. This experimental campaign has been continued with further measurements at the N=Z-line in 2025. Results obtained with the FRS Ion Catcher and published recently also include first results on multi-nucleon transfer reactions at the FRS [12], the demonstration of alpha spectroscopy of thermalised beams of exotic nuclei [13], and mapping the mass surface around N=90, by measuring 64 isotopes with high precision [14]. Addressing even more neutron-rich nuclei was done in a joint experiment at the University of Jyväskylä, where a sudden change in the binding energy of lanthanide isotopes was observed [15].

A spin-off development of the multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) of the FRS Ion Catcher has been built and tailored to the specific opportunities of the TITAN facility at TRIUMF (Vancouver, Canada). This MR-TOF-MS was installed and commissioned at TITAN for the first experiments in 2017. In the past, the mass spectrometer allowed for the discovery of the isotope ^{150}Yb, marking the first isotope discovery with an MR-TOF-MS. Recently, the first-ever mass measurements of the three extremely neutron-rich tin isotopes ^{136}Sn, ^{137}Sn, and ^{138}Sn [16] have been performed with the TITAN MR-TOF-MS. These measurements, combined with nucleosynthesis network calculations (collaboration with GSI theory department), help to better understand how heavy elements are formed in the universe, especially through the rapid neutron capture process (the r-process) occurring in neutron star mergers. The data reveal the neutron separation energy, which defines the path of the r-process on the nuclear chart. The study found unexpected changes in the behaviour of tin isotopes beyond the magic neutron number N=82, specifically, a reduction in the pairing effect of the last two neutrons. In 2025, the successful collaboration with TITAN resulted in more publications on element synthesis [17] and nuclear structure [18][19][20][21][22].

Exotics

This name, which describes one of the 3 priorities of the NUSTAR Collaboration, encompasses several topics: exotic atoms, hypernuclei, and other exotic systems. With the WASA-FRS combination, the Super-FRS Experiment Collaboration has performed in year 2022 experiments addressing these topics. The data analysis has yielded first scientific highlight results: a hint for the existence of bound η'-mesic nuclei and on properties of light hypernuclei. The analysis of data taken with this complex and new setup is very complicated and still ongoing.

The ^{12}C(p,d) reaction was investigated at GSI in the vicinity of the η′-meson emission threshold, with the goal of searching for the formation of η′–^{11}C mesic nuclei. In this experiment, a 2.5 GeV proton beam was used to excite carbon nuclei, leading to the emission of forward-focused deuterons with energies around 1.5 GeV. These deuterons were momentum-analysed using the FRS, operated as a high-resolution momentum spectrometer, allowing the reconstruction of the excitation energy of the residual nuclear system. In addition, the reaction products were measured in coincidence with high-momentum protons using the modified WASA central detector at the FRS. The resulting semi-exclusive spectra reveal distinct structures at excitation energies of approximately −30 MeV and −6 MeV relative to the threshold, as is seen in Figure 41. These features provide evidence consistent with the possible formation of η′-mesic nuclei for the real potential depth of approximately -61 MeV with a local statistical significance of 3.5σ and, taking into account the look-elsewhere effect, a global significance of 2.1σ. The experimental data were analysed within a framework based on a complex optical potential, characterised by a real part V_0 related to the in-medium mass shift and an imaginary part W_0 describing absorption effects. From this analysis, information on the behaviour of the η′ meson in dense nuclear matter could be extracted. In particular, the results indicate a substantial in-medium mass reduction of the η′ meson, quantified as $\Delta m = -61 \pm 1(\text{stat}) \pm 5(\text{syst})$ MeV/c^2 [23].

Concerning the hypernuclei data analysis, the recently employed machine-learning technique improves the signal-to-background ratio significantly [24][25][26]; with this improvement, the determination the lifetimes of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, and the Λ hyperon became feasible: the preliminary values for the obtained lifetimes are 221 ± 39 (stat) ± 17 (syst) ps, 210 ± 30 (stat) ± 10 (syst) ps, and 268 ± 40 (stat) ± 10 (syst) ps. The data give confidence for the further analysis and new results can be expected soon. This improvement is also significant for ongoing, precision spectroscopy of other physical observables, such as the hypernuclear radius [27] and binding energy, which will become accessible.

The data analysis of the performed experiments yielded also new insights for further instrument developments and radiation damage of sensitive detectors [28]. Currently, considerations for forthcoming experiments with a new, more compact setup are underway, and a Technical Design Report for follow-up experiments is in preparation.

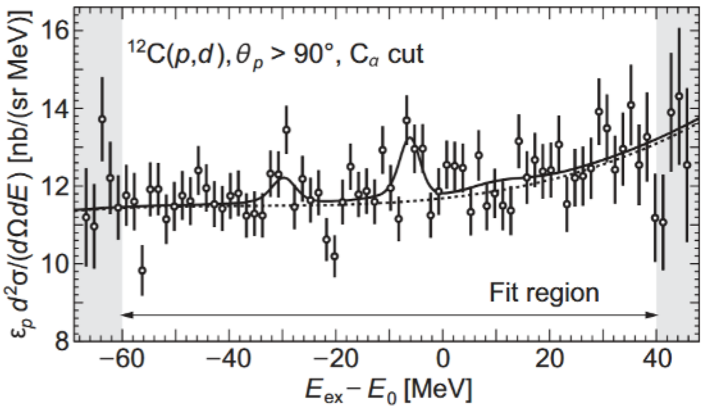

Figure 41: Measured excitation spectrum of the 12C(p,d) reaction near the η'-meson emission threshold E_0. The dotted curve shows the background, while the solid curve is a fit to the data using (V_0,W_0)=(-62,-2) MeV. For details see ref. [23]

Towards multi-nucleon transfer reactions with secondary beams

Worldwide efforts aim at exploring regions of the nuclear chart that remain inaccessible with established methods, in particular neutron-rich heavy isotopes beyond the fission-fragment region (mass numbers A>180) and nuclei with A>235. A promising approach is the use of multi-nucleon transfer (MNT) reactions combined with gas-stopping techniques, enabling the identification and study of the produced ions. Within the Super-FRS Experiment Collaboration, it is a long-term objective to exploit MNT reactions with intense neutron-rich beams at FAIR. Current activities include studies with stable beams at Coulomb-barrier energies, tests with slowed-down SIS-18 beams, and close interaction with theory to benchmark reaction models. Significant progress has recently been achieved at the FRS Ion Catcher, where MNT products were produced and identified using decelerated relativistic beams (experiments G-22-00117 and G-22-00179). In this setup, a ^{238}U beam was reacted with a ^{209}Bi target in a cryogenic stopping cell, and the resulting products were analysed with a multiple-reflection time-of-flight mass spectrometer. The successful identification of target-like fragments provides an important proof of principle for future MNT studies with secondary beams [12].

Technical developments for new experiments at the Super-FRS

Many developments are underway and made significant progress; here, two of them will be mentioned. Significant progress has been made in the technical development of the Cryogenic Stopping Cell (CSC) for the Super-FRS Ion Catcher. The Technical Design Report has been published [29]. In parallel, refined and optimised technical specifications for the CSC vacuum chambers have been completed, consolidating the engineering basis of the CSC and clearing the path for tendering. The procurement of the cryocoolers, the core cryogenic components ensuring the CSC's full planned cooling capacity, has been successfully completed. A project was initiated to evaluate the radiation-induced damage of the CSC electronics under Early Science and First Science conditions, with the aim of developing effective mitigation solutions. Technical developments also advanced across several supporting systems: a prototype of the next-gen RF generation system for the RFQ beamline and mass filters has been realised; an investigation into long-term high-amplitude operation of the RF carpet has been started to define safe operating boundaries. The development of beam tracker and range scanner detectors has commenced to support experiments with stopped beams. Finally, initial steps toward enabling laser spectroscopy studies at FHF1 have begun, setting the stage for conducting experiments of the LaSpec collaboration ahead of the full Low-Energy Branch implementation.

A further key component for Early-Science and First-Science phases at the Super-FRS at FAIR is the EXPERT detector system, which is designed for flexible integration into the central focal plane of the Super-FRS. A basic configuration is already available and has been successfully employed in pilot experiments at the FRS during FAIR Phase-0. These studies will allow for the investigation of the limits of existence of nuclear structure using the original in-flight decay technique, as described above. A case for the first experiments at the Super-FRS is for instance the decay of the ^{13}F decay into ^{10}C+3p, which will be detected by coincident tracking of the trajectories with silicon micro-strip and pixel detectors. The measured angular correlations of the 3p-decay products will allow to address nuclear structure at the proton dripline and a test of isospin symmetry breaking.

Outlook 2026

The activities of the department are closely aligned with and firmly integrated into the NUSTAR schedule for Early Science and First Science, respectively. The upcoming experiments at the Super-FRS will open new frontiers in the study of exotic nuclei. While the construction of the Super-FRS facility progresses, the department members as integral part of the Super-FRS Experiment Collaboration exploit several new detectors and instruments already at the existing GSI accelerator facility. The overarching key objective is the understanding of the third r-process abundance peak through nuclear structure systematic studies around the neutron shell closure at N = 126, the exploration of the limits of nuclear stability at the proton and neutron driplines, as well as studying the equation of state of asymmetric nuclear matter via skin and radii measurements, and the exploration of exotic nuclear systems like hypernuclei or mesic atoms. Next to the science, an important infrastructure goal is to maintain the separator as source of relativistic exotic nuclear beams for experiments, in particular at the ESR/CRYRING storage-ring complex, as outlined in the roadmap for the next Program-Oriented Funding period V (POF-V, 2028–2034) within the Helmholtz research area "Cosmic Matter in the Laboratory".

Acknowledgements

We sincerely acknowledge the continuous and collegial support provided by all departments and their staff. In particular, we would like to highlight the contributions of the Detector Laboratory, Target Laboratory, IT and EE departments, Beam Diagnostics, ACO, Netzgerätegruppe, Großmontage, PMO-PPL, and especially the ion-source and accelerator teams together with the operators. Their expertise and dedication have been essential for the successful realization of all experiments and the results presented here.

This appreciation extends equally to the engineers, technicians, and student trainees of the FRS/Super-FRS Experiments department, whose efforts have been indispensable. We also gratefully acknowledge the valuable contributions of our collaboration partners and visiting scientists.

A special mention goes to the NUSTAR Beam Team, which played a central role in the preparation and execution of the experiments. We are deeply grateful to all team members for their commitment, as well as to the many collaborators whose support was crucial for the successful implementation of the program.

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4.3 Nuclear reactions

Head: Prof. Dr. Thomas Aumann (Technical University Darmstadt & GSI)

Authors: Thomas Aumann & Valerii Panin

Introduction

The department Nuclear Reactions develops and operates the R^3B (Reactions with Relativistic Radioactive Beams) experiment, which allows for kinematically complete measurements of reactions with heavy-ion beams with typical energies of 0.5 to 1 GeV/u. The scientific aim is to determine and understand the properties of neutron-proton asymmetric nuclei and nuclear matter, the properties of astrophysical objects like neutron stars, as well as nucleosynthesis processes in stars, stellar explosions, and neutron-star mergers by measuring reactions with short-lived nuclei. A start version of the FAIR R^3B experiment has been installed in Cave C at GSI, while completion of the detector construction is still ongoing.

Constructions and tests

During 2025, construction and tests of several fibre detectors for tracking, including those for the proton-arm spectrometer PAS, have progressed. PAS will be installed in the big vacuum chamber behind GLAD for large-acceptance tracking and momentum determination of protons and other light charged particles emitted with magnetic rigidities smaller than that of the beam. In addition, the construction of a new fast time-of-flight wall based on Si-PM readout has progressed, as well as the further construction of NeuLAND double-planes. The construction of the HYDRA prototype TPC for tracking in the GLAD magnetic field has been accomplished, including beam tests at CERN and the integration of the DAQ system into the R3B framework. The detector will be used for an experiment in 2026 to measure the total interaction cross section of the hypertriton, which will reveal its hyper-halo structure.

Experiments

During 2025, two experiments within the FAIR Phase-0 beamtime have been successfully conducted.

ASY-EOS II: Constraining the symmetry energy at high density.

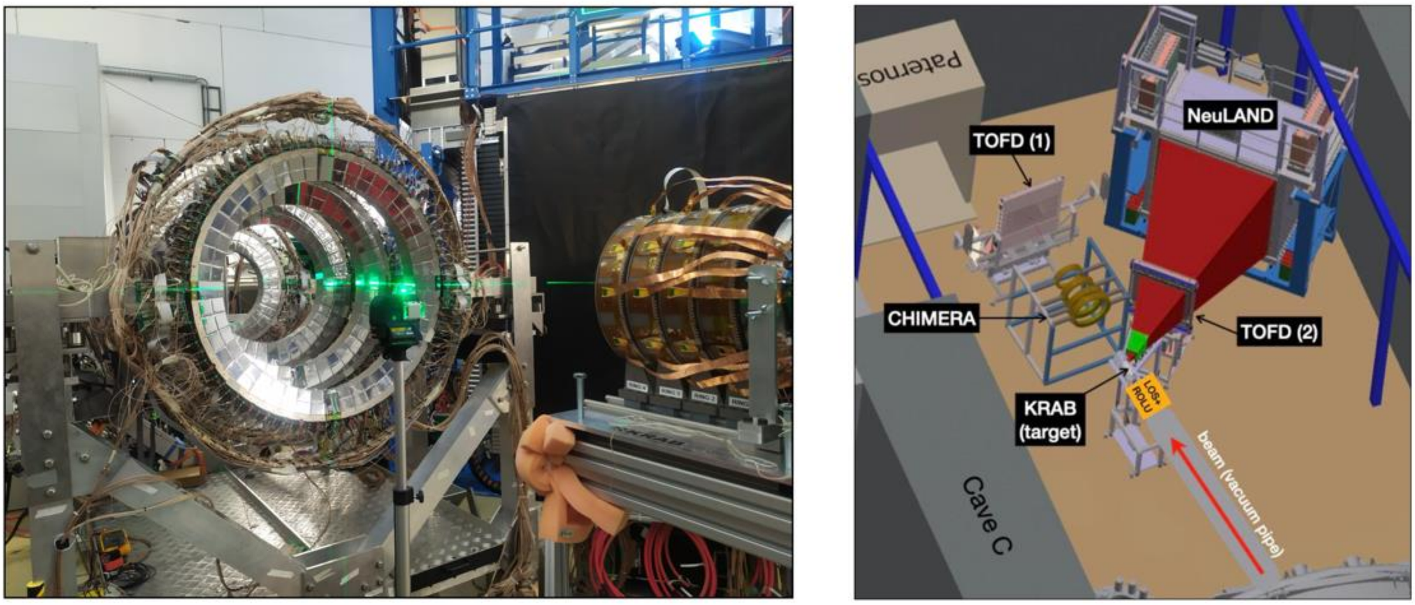

Figure 42: Experimental setup in Cave C of the ASY-EOS II experiment. Left picture: view on CHIMERA (left), KRAB (right), TOFD, and NeuLAND detectors. Right picture: top view of the full experimental geometry, including R3B detectors such as NeuLAND and TOFD.

The first experiment was devoted to the measurement of Au+Au collisions in a wide energy range (ASY-EOS II experiment). The aim is to derive more stringent constraints on the density dependence of the symmetry energy at supra-saturation densities, which has strong implications on the knowledge of neutron star properties such as their mass-radius relation. It is done from the excitation function of the neutron/proton elliptic-flow ratios in an incident energy range from 280 to 1000 MeV/u. For this purpose, a dedicated experimental setup was configured in Cave C, comprising several additional detection systems such as CHIMERA array of 320 CsI(Tl) crystals and KRAB scintillating-fibre array, as shown in Figure 42. This was achieved through the coordinated effort of a large international collaboration led by researchers from INFN-LNS (Italy), IFJ-PAN (Poland), R3B-GSI, and other institutes from France, Italy, USA and Japan. The new detectors were successfully transported from Catania and Krakow to GSI, and were fully integrated into the R3B environment, including DAQ and online monitoring.

The high-quality Au beams, provided by the GSI accelerator group, combined with stable operation and an optimised spill structure, enabled the collection of high-fidelity data and enhanced statistics during the two-week data-taking period.

The data analysis is on-going since Summer 2025, and will continue in 2026. It already delivered promising preliminary results fulfilling the expectations of a much-improved accuracy in comparison with the ASY-EOS I (S394) measurements of May 2011.

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreements no. 824093 (STRONG2020), and no. 101057511 (EURO-LABS).

Investigation of the properties of deeply bound protons in the vicinity of the neutron dripline

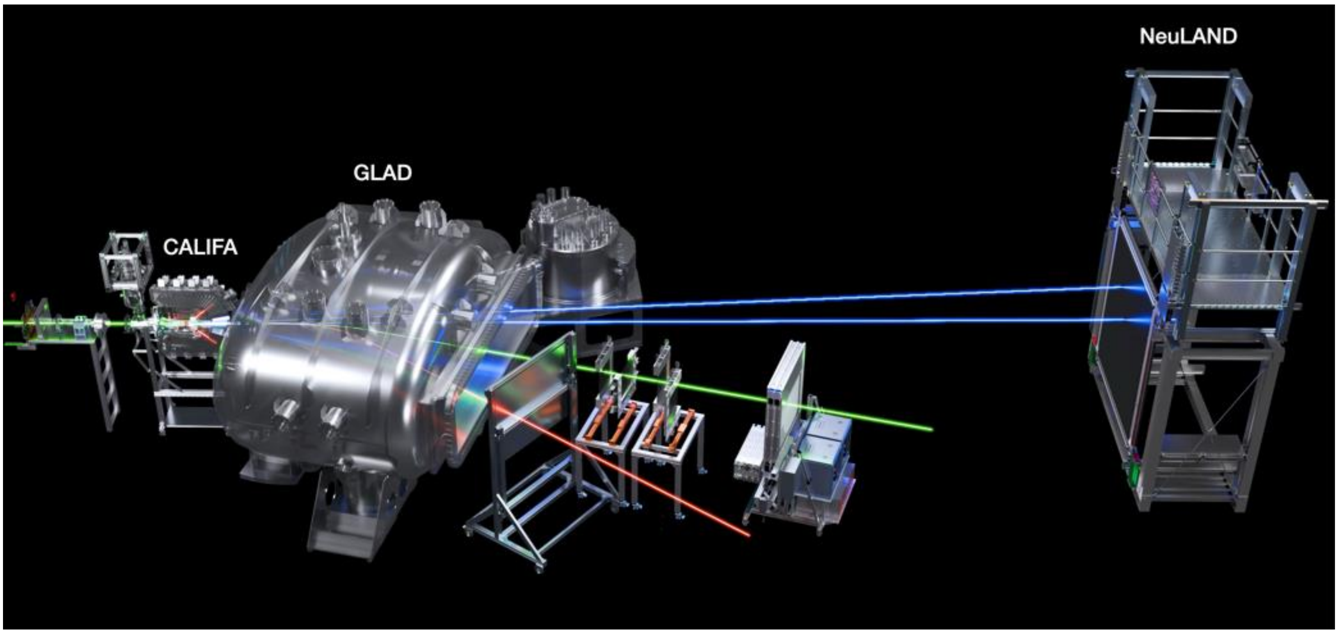

Figure 43: R3B setup for the G-24-00249 experiment in 2025. The coloured lines depict trajectories of the beam and heavy fragments (green), neutrons (blue), and protons (red) through the magnetic field of the superconducting spectrometer GLAD. The (p,2p) and (p,pn) reactions in a liquid-hydrogen target were measured by the surrounding CALIFA calorimeter for protons and gammas, while NeuLAND was used to detect one or multiple outgoing neutrons from decay of neutron-unbound final states.

The second experiment (G-24-00249) used a cocktail of unstable neutron-rich nuclei, produced at the fragment separator, to investigate the properties of deeply bound protons in the vicinity of the neutron dripline by means of proton-induced knockout reactions (p,2p) and (p,pn) at an energy around 630 MeV/u. Several fluorine isotopes ^{22,23,24,25}F were used to examine anomalous spectroscopic factors of valence protons as the neutron number approaches the magic N=16, as well as to study the effect of the tensor force on the single-particle energy levels in isospin-asymmetric systems. The reactions were induced inside a 50 mm liquid-hydrogen COCOTIER target surrounded by a CALIFA calorimeter. A substantial upgrade of the in-beam tracking system by several ALPIDE pixel sensors and FOOT SSDs enabled high-accuracy measurements of the outgoing reaction products and a reconstruction of the reaction vertex inside the target. The full experimental setup is shown in Figure 43.

The unique capabilities of the R3B setup to perform kinematically complete measurements are exploited to reconstruct the reactions in a fully exclusive manner. This approach enables the determination of the invariant mass and, consequently, the energy of unbound final states. Figure 44 presents the identification of the ^{25}F(p,2p)^{24}O reaction channel, based on information from CALIFA and fragment tracking with the silicon trackers and other detectors, which are used to reconstruct trajectories of the heavy fragments through the GLAD magnet.

The ongoing analysis of the relative-energy spectra with one and multiple neutrons will provide further details on the spectroscopy of the deeply bound proton orbitals along the Z=9 isotopic chain. Thanks to the versatility of the R3B detection systems and the cocktail beams, several other reactions will be explored in the following analysis, which will help to broaden our understanding of the dripline phenomena in this region of the nuclear chart. The international R3B collaboration for this experiment comprised many young and senior researchers from several European institutes under the support of EURO-LABS: European Union’s Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

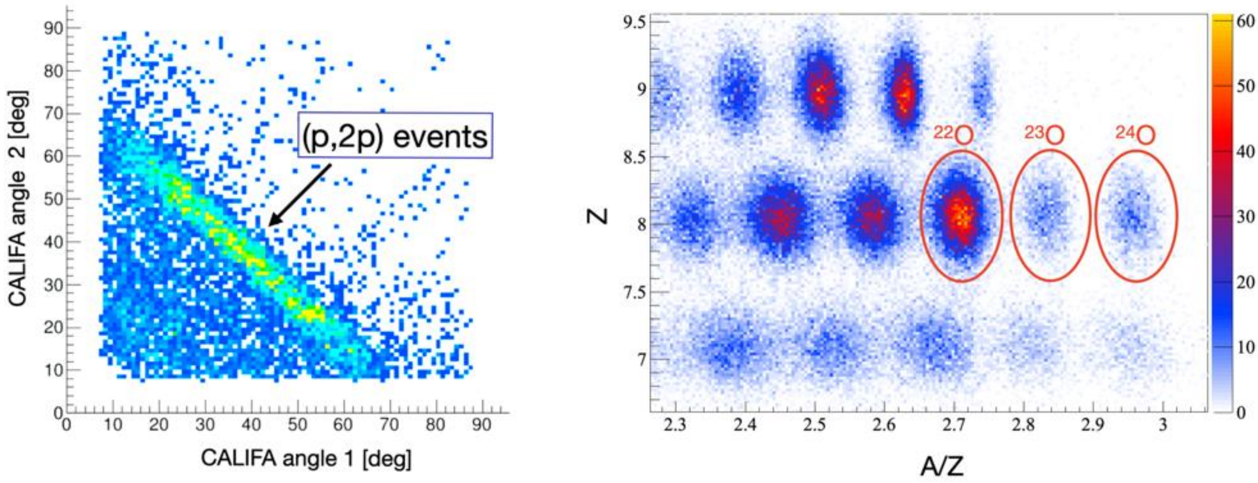

Figure 44: Identification of the reaction channels with the incident ^{25}F beam. Left figure: correlation between polar angles of the two protons in CALIFA. The diagonal structure is the kinematic signature of (p,2p) reactions. Right: Identification of the outgoing heavy fragments in coincidence with the (p,2p) or (p,pn) signal in CALIFA. Different oxygen isotopes correspond to the reaction channels with none, one, or multiple neutrons emitted from the populated final states of the dripline nucleus ^{24}O.

Highlight in 2025

Discovery of an "asymmetric fission island" in neutron-deficient nuclei

Authors: Pierre Morfouace, Julien Taieb (CEA, Arpajon; Université Paris-Saclay; CEA, Bruyères-le-Châtel, France)

In 2025, researchers at GSI Helmholtzzentrum für Schwerionenforschung, together with international collaborators, achieved a major breakthrough in the understanding of nuclear fission. Their results were published in *Nature* under the title "An asymmetric fission island driven by shell effects in light fragments" [1]. The study reveals the existence of a previously unknown region of asymmetric fission in light, neutron-deficient nuclei, fundamentally expanding the established picture of how atomic nuclei split.

For decades, pronounced asymmetric fission, where a nucleus splits into two fragments of unequal size, had been regarded as a characteristic feature of heavy actinide nuclei. In these systems, quantum shell effects in the fragments are known to favour specific mass partitions. In contrast, lighter nuclei were generally expected to undergo symmetric fission, following macroscopic liquid-drop behaviour.

The present work overturns this long-standing assumption. Through a comprehensive and systematic investigation of nearly one hundred exotic nuclei in the sub-lead region, From Iridium to Thorium isotopes, the R^{3}B collaboration discovered a distinct "island" in the nuclear chart where asymmetric fission dominates, as displayed in Figure 45. This island is driven by microscopic shell effects in the nascent fragments, most notably by a deformed proton shell at atomic number Z = 36. The data demonstrate that structural quantum effects, rather than purely macroscopic properties, govern the fission process in this region, establishing an unexpected structural link between light neutron-deficient systems and the well-known asymmetric fission of heavy actinides.

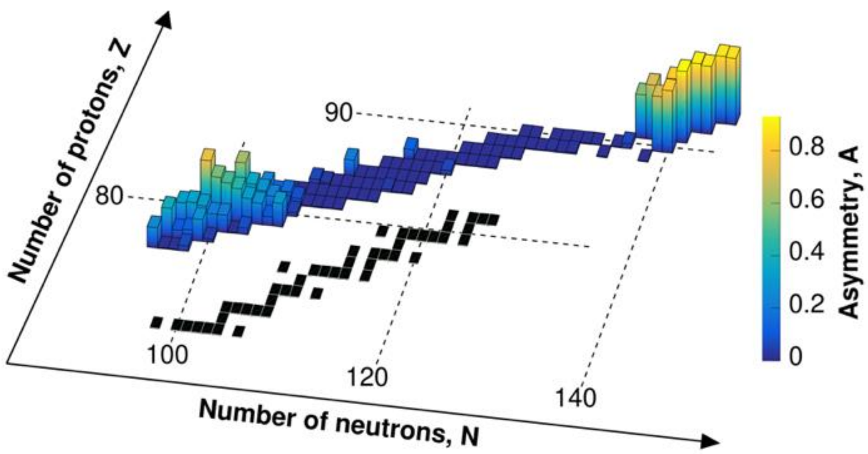

Figure 45: While chemical elements differ by the number of electrons they have, atomic nuclei are characterised by the number of neutrons and protons. Here the investigated nuclei are marked in colour, differing from stable isotopes which are found in

nature (marked in black). The colour also indicates how fission happens, the higher a column, the larger the difference is the mass difference of the two fission fragments. Illustration: Pierre Morfouace, CEA, DAM, DIF, Arpajon, France.

Unique experimental capabilities at GSI

This discovery was made possible by the unique experimental infrastructure at GSI. The combination of high-intensity heavy-ion beams, state-of-the-art fragment separation techniques (thanks to the large superconducting magnet GLAD; see Figure 46), and precision detection systems enabled the production and identification of rare neutron-deficient isotopes far from stability. The experimental campaign delivered an unprecedented dataset of fission-fragment charge distributions, many of them measured for the first time.

The work highlights GSI's long-standing expertise in fragmentation reactions, rare-isotope identification, and high-resolution spectroscopy. By pushing experimental access toward the limits of the nuclear landscape, GSI continues to provide essential benchmarks for state-of-the-art theoretical models of nuclear structure and fission dynamics.

Beyond its fundamental importance, the discovery has broader implications. A deeper understanding of fission fragment distributions is crucial for modelling nucleosynthesis processes in extreme astrophysical environments, where fission recycling can shape the abundance of heavy elements. The new results therefore provide important constraints for global theoretical descriptions of fission across the nuclear chart.

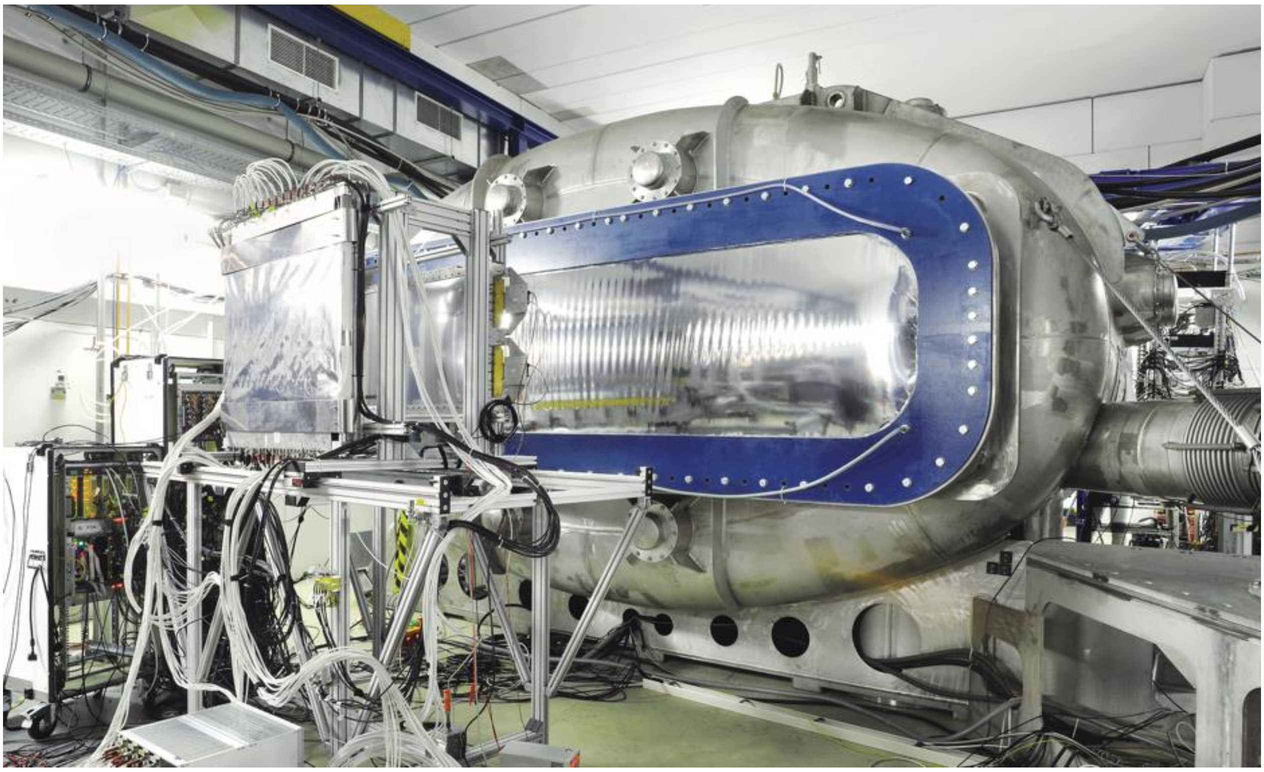

Figure 46: A photograph of the experimental setup used for this study, dominated by the large superconducting magnet GLAD. Photo: G. Otto/GSI/FAIR.

Outlook: Extending the frontier with FAIR

The discovery of this asymmetric fission island marks only the beginning of a systematic exploration of shell-driven fission phenomena in exotic nuclei. The upcoming Facility for Antiproton and Ion Research will significantly expand the accessible regions of the nuclear chart, enabling studies of even more neutron-deficient and neutron-rich systems with higher precision and intensity.

The 2025 Nature publication thus represents both a scientific milestone and a strategic stepping stone toward the next generation of discovery at FAIR.

Outlook 2026

During 2025, the construction of the HYDRA prototype TPC for tracking in the GLAD magnetic field has been accomplished including beam tests at CERN and the integration into the R^{3}B DAQ System. A first experiment to produce and study properties of hypernuclei is planned as the last R^{3}B FAIR Phase-0 experiment in 2026 before start moving GLAD to the high-energy cave at FAIR behind the Super Fragment Separator. The experiment will measure the production cross section of the hyper triton as well as its total interaction cross section. The HYDRA TPC will serve as a pion tracker in the magnetic field. Fragments will be tracked and identified behind the GLAD magnet which will allow an invariant-mass analysis. The total interaction cross section will inform on the radial size of the hyper triton, which is expected to exhibit a hyper-halo caused by the small separation energy of the lambda.

Selected publication of 2025

[1] P. Morfouace *et al.*, "An asymmetric fission island driven by shell effects in light fragments," *Nature*, vol. 641, pp. 339–344, Apr. 2025, doi: 10.1038/s41586-025-08882-7.

4.4 Nuclear spectroscopy

Head: Dr. Magdalena Górska (GSI)

Authors: Magdalena Górska, Helena May Albers, Jürgen Gerl, Kathrin Wimmer

Introduction

The structure of atomic nuclei is investigated in the Nuclear Spectroscopy Department (KSP) through studies of excited states and their decay. Using comprehensive high-resolution gamma-ray and charged-particle spectroscopy of selected key isotopes, the evolution of shell structure and exotic nuclear shapes near the limits of nuclear existence, as well as their relevance for the nucleosynthesis of heavy nuclei, are explored.

The department continuously develops the detectors, instrumentation, and associated experimental methodologies required for spectroscopic investigations. The transfer of technologies arising from this development work is actively pursued for the benefit of society. Many activities are carried out in close collaboration with international partners within the HISPEC/DESPEC, AGATA, MINIBALL, and other collaborations, as well as through leading ERC grant LISA and a sub-project of the EURO-LABS consortium (INTRANS).

The department coordinates the activities of the HISPEC/DESPEC collaboration and is responsible for the coordination of the development and construction of the related infrastructure for experimental campaigns at GSI and FAIR. Two main experimental approaches are employed to address the physics goals: the in-beam method, in which prompt gamma rays and reaction products from nuclear reactions are measured (HISPEC), and the decay method, in which the properties of radioactive ions decaying at rest are analysed (DESPEC). Both types of experiments are performed at GSI/FAIR and at other international facilities such as RIBF, LNL, and ISOLDE. While DESPEC experiments are routinely scheduled at GSI, HISPEC in-beam spectroscopy experiments at FAIR are currently in the preparatory phase.

Highlights in 2025

LISA active target commissioned

The LISA (Lifetime measurements with Solid Active targets) project, funded by the European Research Council and led by our group, aims at the development of a novel active target system based on layered arrays of single-crystalline diamond detectors. The LISA concept combines the advantages of solid targets with active detector capabilities, providing excellent energy resolution and enabling particle and reaction identification through precise energy-loss measurements of heavy ions traversing the detector layers.

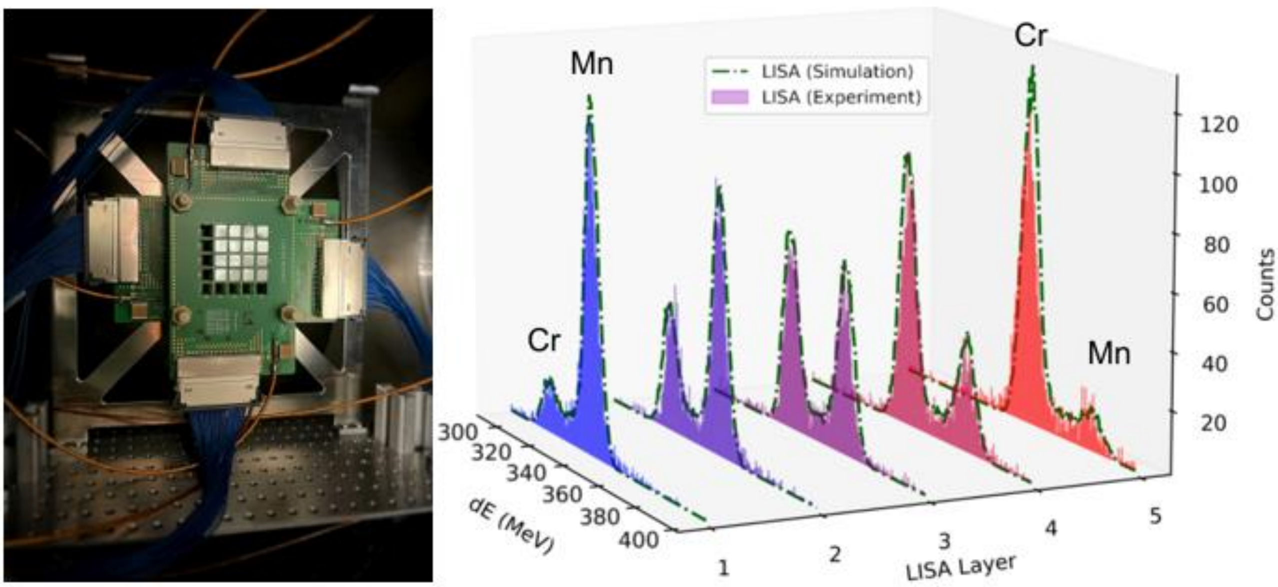

Figure 47: Installation of five LISA target layers at the S2 focus of the FRS (left). Reaction identification with LISA, incoming ^{50}Mn particles were selected suing the FRS (right). Passing through the five layers, the intensity of ^{50}Mn diminishes while one-proton knockout reaction products ^{49}Cr increase in intensity.

During the reporting period, major milestones in the development of the LISA active target were achieved. Custom readout electronics were designed and produced, and an extensive acceptance test and characterization campaign was carried out for 125 diamond detector crystals. Based on these results, a full target array consisting of five detector layers was assembled and successfully commissioned in beam.

The commissioning experiment took place in May 2025 at GSI. The five LISA target layers were installed at the S2 focal plane (see Figure 47 left) of the Fragment Separator (FRS), with standard particle identification detectors positioned upstream and downstream of the active target. This configuration enabled unambiguous identification of incoming ions as well as reaction products produced within the target volume.

The performance of the active target was demonstrated using one-proton knockout reactions from an identified 50Mn beam. By measuring the energy loss of particles in each of the five layers, LISA allows both reaction-channel identification and localization of the reaction vertex within the target. As the beam passes through successive layers, the intensity of the primary 50Mn beam decreases, while the intensity of the reaction products (^{49}Cr) correspondingly increases, clearly illustrating the active-target concept (see Figure 47 right).

The commissioning experiment provided important information on the rate capability of the system, the stability of the custom electronics, and the long-term behaviour of the diamond detectors. Overall, the results confirm that the LISA active target performs as designed and is ready for future physics experiments. Technical publications describing the detector system are in preparation, and the commissioning data will also be used to explore the feasibility of using LISA for reaction cross-section measurements.

DESPEC Implantation setup test

The core of the DESPEC setup for radioactive-ion-beam implantation and nuclear decay studies was tested in early 2025 using an alternative detector geometry and electronics configuration. Although the full characterization of the final setup is still ongoing —including the evaluation of alternative solutions depending on the specific physics case — preliminary results from the test experiment are presented in Figure 48.

A fragmentation reaction of a ^{107}Ag beam on a ^{9}Be target was used to produce neutron-deficient nuclei along the N = Z line below ^{100}Sn. In particular, the superallowed decay of ^{82}Nb, produced in this reaction, was investigated using two types of DSSSD detectors.

Figure 48 (top) shows the lifetime obtained with the AIDA detector system, while the right panel presents the result from the BB7-type DSSSD operated with AIDA electronics. Both extracted lifetime values are consistent with the literature value within uncertainties.

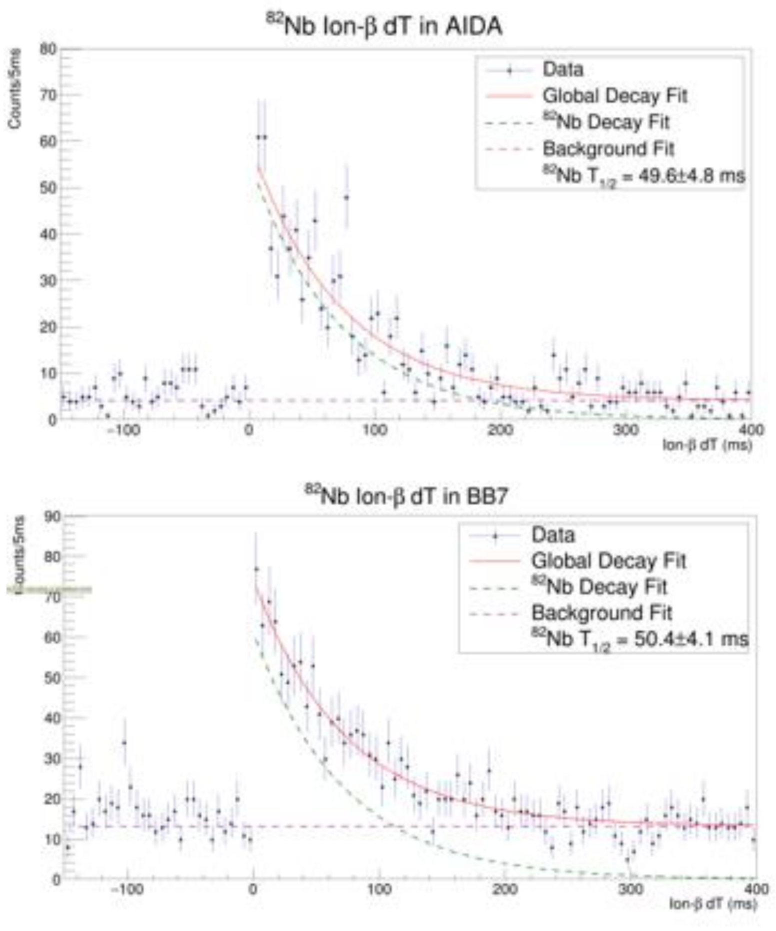

Figure 48: Lifetime determination test of the ^{82}Nb beta decay using AIDA (top) and BB7 (bottom) DSSSD detector.

Machine learning used for DESPEC active stopper

Key aspects of the DESPEC physics program relies on the use of active stoppers into which exotic ion species of interest are implanted and their decay products are subsequently observed. Recent work within the Nuclear Spectroscopy Group has focused on investigating the position resolution of the DESPEC bPlast plastic scintillator detectors for incident heavy ions. A novel method wherein interaction positions were extracted via k-nearest neighbour, non-generalizing search methods using a highly-segmented double-sided silicon strip detector (AIDA) to provide reference samples was successfully implemented. The data used in the study was collected during DESPEC FAIR Phase-0 experiment S460 at the S4 area of the GSI Fragment Separator (FRS). Resolutions of $\sigma < 1.5$ mm in both X and Y directions were achieved by employing a KD-Tree search method with a Euclidean metric. It is shown exemplary in Figure 49.

The manuscript describing the methodology and results was accepted for publication in December 2025 and since been published in the Journal of Instrumentation [1].

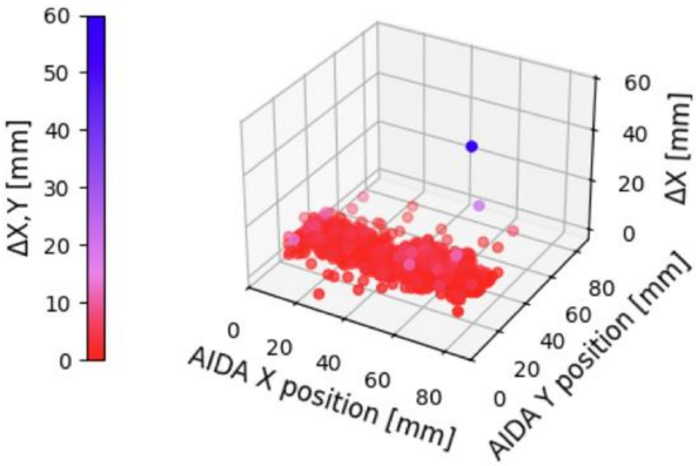

Figure 49: 3-dimensional plots of the X hit positions recorded by the AIDA reference DSSD for heavy ion event versus the difference between the reconstructed positions on the bPlast detector and reference hit positions in X (ΔX).

DESPEC experimental result near ^{100}Sn

The lifetimes of low-lying excited states below the 8^+ seniority isomer were directly measured using fast-timing detectors in the neutron-deficient isotopes ^{98}Cd and ^{100}Cd with the DESPEC setup. In particular, the lifetimes of the 4^+_1 state in ^{98}Cd and the 4^+_1 and 6^+_1 states in ^{100}Cd were measured directly for the first time [2].

Single-particle and collective degree of freedom in neutron-rich Ca isotopes

As part of a DFG SFB-funded project, the single-particle structure of the neutron-rich isotope ^{51}Ca was investigated via the ^{50}Ca(d,p) transfer reaction in inverse kinematics at RIBF/RIKEN. Using a decelerated radioactive ^{50}Ca beam from the OEDO facility in combination with the $TiNA_2$ silicon array and the SHARAQ magnetic spectrometer, excited states in ^{51}Ca were populated and studied through missing-mass spectroscopy. Angular distributions of emitted protons were measured and analysed using ADWA calculations to extract spectroscopic factors for the ground state and several excited states. Comparison with shell-model and ab initio VS-IMSRG calculations supports the assignment of the $1/2^-$ and $5/2^-$ single-particle states and provides evidence for a candidate $9/2^+$ state associated with neutron excitation into the $0g_{9/2}$ orbital.

These results provide new constraints on shell evolution in neutron-rich calcium isotopes and have just been accepted for publication in Phys. Rev. C.

To deepen the understanding of the evolution of single-particle strength and collective excitations in neutron-rich Ca isotopes, including octupole excitations, a series of inelastic scattering experiments was performed for $^{50-54}$Ca and ^{49,51}K isotopes at RIKEN in June 2025 using the DALI2+ and HYPATIA detector arrays. The experiments were very successful, with the identification of quadrupole and octupole excitations in all investigated isotopes. The data analysis is ongoing.

First high-resolution in-beam gamma-ray spectroscopy of neutron-rich Mo isotopes at relativistic energy

Triaxial deformation in neutron-rich Mo isotopes was investigated through the first high-resolution in-beam gamma-ray spectroscopy measurements of ^{110}Mo and ^{112}Mo at relativistic energies at the RIBF facility at RIKEN. The isotopes were produced via nucleon-removal reactions and studied using the HiCARI detector array. Doppler-corrected spectra allowed precise determination of transition energies and lifetimes using the line-shape method. The level scheme of ^{112}Mo was significantly extended, including the gamma-band structure, and reduced transition probabilities were extracted [3]. The results indicate strong collectivity and increasing triaxial deformation toward N=70, in good agreement with modern theoretical models.

The Artemis project

The EU-funded artEmis project deals with the development of an earthquake early-warning sensor network, based on sophisticated groundwater measurements. The KSP team is responsible for the development and realization of the sensors system. In previous reports from 2022, 2023 and 2024, the concept and early implementation of a series of systems has been reported. The experience gained with the pre-series systems triggered targeted developments leading to substantial improvements and adaptations of the hardware and firmware in the reporting period.

In particular, unexpected problems with the stability/quality of the power connection in many sites in Greece and Italy made a revision of the concept necessary. This led also to a revision of the deployment strategy. Instead of relying on the originally planned advanced demonstrator as final product, which would be mass produced in one step after cross-checking the performance of a pre-series, it was decided to produce batches of sensor systems over the whole duration of the project. This allows further improvements and adaptations and fits better to the available person power and funding situation. Production and deployment of the new batches started in Spring 2025.

The core of the sensor device is a CsI(Tl) scintillation detector to efficiently detect gamma radiation. The scintillation light is being read out by silicon photomultipliers (SiPMs). Highly-integrated signal forming and processing electronics is arranged in the detector units. Adequate computing power is available on-board of the detector unit as well as bias generators, environmental controls like temperature sensors, and appropriate communication channels. Here, the project relies on the latest electronics and data acquisition developments available from our nuclear physics experiments. The mechanical structure of the sensor-unit has been optimised for underwater operation in the wanted depth range with further activities going on.

Gamma energy spectra and other sensor's information is collected and transmitted in suitable intervals, e.g., every ten minutes for further analysis employing control units coupled to a network. Employing either mobile net routers or LAN, data is sent via internet to an MQTT server operated by our partners at KTH, Sweden.

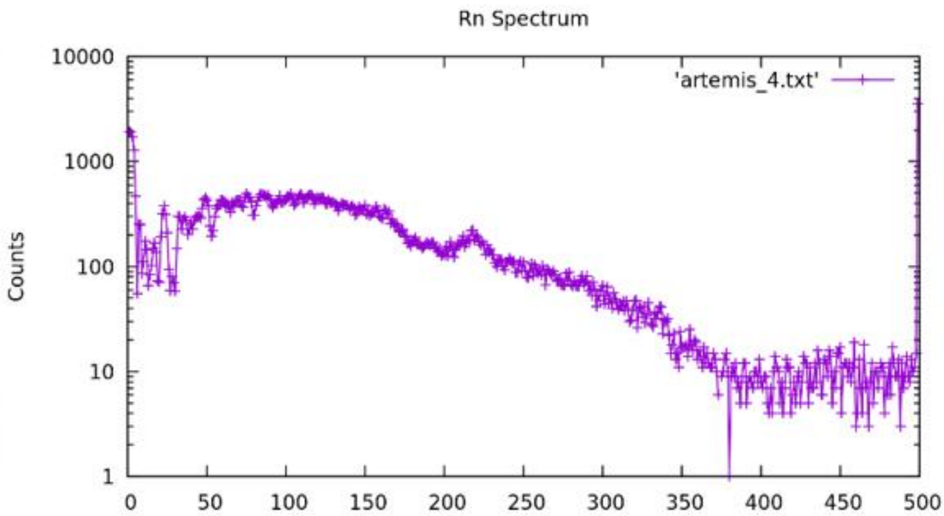

Figure 50: Sensor unit deployed in a well in Brunello (island of Lefkada), Greece (left). A typical radon gamma-ray spectrum in keV units from this site (right).

About 20 new systems were installed successfully in 2025 and the experience gained turned out to be very useful. Figure 50 shows an example of a well with a sensor installed. The shown radon gamma-ray spectrum was obtained within a few minutes. As expected for in-water measurements, it is dominated by Compton events, but still the most prominent 609 keV line (around channel 220) is visible. It serves mainly as gain control, while the radon rate can be directly determined from the full spectrum, containing only a few percent environmental background. Therefore, an outstanding sensitivity of < 1Bq/l/h is reached [4].

The early demonstrator systems suffered from too frequent down times due to blackouts and glitches of the electrical supply power. The novel advanced sensor units overcome this deficiency by auto-recovery, minimizing down times. The new sensor systems are being deployed by local teams almost independently from our experts. Figure 51 demonstrates the reliability of the measurements since. The prominent spike structures in July, September, October and November are correlated with seismic events which took place 2-3 days later in locations about 200 and 25 km away. Including further sites to a network of sensor stations aims at determining the epicentres of earthquakes with the help of AI/ML methods.

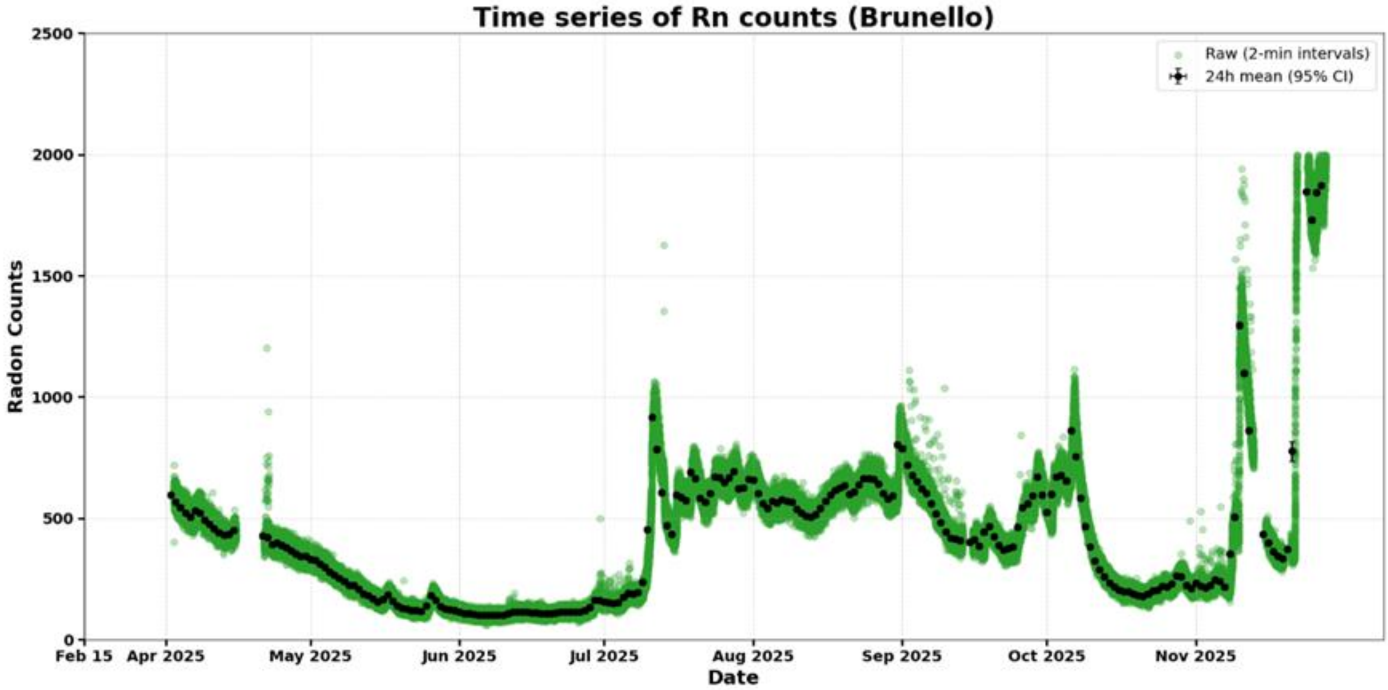

Figure 51: Time series of the measured radon activity of the Brunello well since its start in April 2025.

Outlook 2026

The experimental work and data analysis from 2025 have been or will be summarised in upcoming publications. A number of new experiments—in various facilities including dedicated test runs—are planned to prepare the experimental apparatus for the FAIR Early and First Science program.

With advancements in machine learning techniques, the performance of specific detectors will be further analysed. Experiments at other facilities are expected to continue throughout 2026, focusing on the spectroscopy of exotic nuclei.

Selected publications of 2025

[1] H. M. Albers and M. Polettini, "Position reconstruction of heavy-ion interactions in plastic scintillator detectors," Journal of Instrumentation, vol. 21, no. 1, p. P01024, Jan. 2026, doi: 10.1088/1748-0221/21/01/P01024.

[2] G. Zhang et al., "Approaching 100Sn: Structural evolution in 98,100Cd via lifetime measurements," Physics Letters B, vol. 863, p. 139378, 2025, doi: 10.1016/j.physletb.2025.139378.

[3] B. Moon et al., "First high-resolution in-beam γ-ray spectroscopy of neutron-rich Mo isotopes at relativistic energy," Physics Letters B, vol. 870, p. 139904, 2025, doi: 10.1016/j.physletb.2025.139904.

[4] Kumar, Gururaj et al., "Earthquake precursor measurements employing a network of radon sensors," EPJ Nuclear Sci. Technol., vol. 11, p. 48, 2025, doi: 10.1051/epjn/2025045.

4.5 Superheavy elements at GSI and HI Mainz

Head: Prof. Dr. Christoph E. Düllmann (Johannes Gutenberg University Mainz, Helmholtz Institut Mainz & GSI) and Prof. Dr. Michael Block (Johannes Gutenberg University Mainz, Helmholtz Institut Mainz & GSI)

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Introduction

The focus of the experimental work of the superheavy element departments in 2025 was on running experiments within the user beamtime served at GSI. Nuclear spectroscopy studies at TASCA focused on the ^{288}Mc decay chain, while laser spectroscopy experiments at SHIP focused on the structure of the longer-lived known K-isomer in ^{254}No and on neutron-deficient Cf nuclei. Additional activities at GSI focused on the analysis and publication of data obtained previously, both at GSI as well as abroad, e.g., at NPI CAS Řež (CZ). Main results from TASCA include a mapping of the shoreline of the island of enhanced stability in the region of Rf and Sg, including the discoveries of the most short-lived known superheavy nucleus, 60-ns ^{252}Rf and the new neutron-deficient ^{257}Sg, and the first observation of K-isomerism in Sg, which paves the way towards yet unknown yet shorter-lived Sg nuclei on the shoreline. Chemistry studies of Tl and Po, which are the lighter homologs of the superheavy elements Nh and Lv, were performed at NPI CAS Řež (CZ), supported by theoretical studies at GSI. Furthermore, offline work as well as technical and method developments to break current frontiers in future beamtimes to increase production rates, to advance to heavier, more exotic systems, to gain access to new observables and to provide higher-quality data were carried out at GSI and at HIM.

Synthesis / Nuclear Reactions

The dynamics of nuclear fusion reactions leading to the formation of the superheavy nuclei remain an interesting topic in the field. The fusion probability in heavy-ion induced reactions with actinide targets is strongly suppressed by competing processes taking place prior to fusion such as quasi-fission and deep inelastic scattering, which involve the exchange of a fraction of the nucleons of the reactants. Quasi-fission is widely believed to be responsible for the emission of heavy fragments with masses around ^{208}Pb by the composite system. Theoretically, this feature has been attributed to the presence of a ^{208}Pb valley on the potential energy surface of superheavy nuclei. The origin of the ^{208}Pb peak in the mass distribution of quasi-fission fragments was investigated in a collaboration of the SHE Chemistry departments at GSI and HIM and the nuclear reactions group at the Australian National University (ANU), Canberra, Australia, at the Heavy Ion Accelerator Facility of ANU. Building up on prior work, the results [1] showed that the quasi-fission alone cannot explain the observed ^{208}Pb peak but that sequential fission of heavy fragments above ^{208}Pb should also be considered. This collaborative work has been continued in a systematic study of the ^{208}Pb effect [2]. The results confirm that the present understanding of the ^{208}Pb effect on the mass distribution of fission fragments from heavy-ion induced reactions is still far from complete. Further experimental and theoretical studies are therefore needed for a correct interpretation of the ^{208}Pb effect, which is crucial for further superheavy element syntheses.

Nuclear Structure

At the SHE Chemistry department, intensive research to map the isotopic border in the region of the heaviest nuclei and to study their fission properties is successfully ongoing. After the discovery of the shortest-lived known superheavy nucleus, ^{252}Rf [3] the research program at the gas-filled recoil separator TASCA was focused on exploring the K-isomer phenomenon and the isotopic border for the next heavier even-Z element, Sg. As a result, the new isotope ^{257}Sg, with a half-life of about 12 ms, which decays by both fission and α-particle emission, was discovered by using the ^{52}Cr high-intensity UNILAC beam on ^{206}Pb targets. Evidence for a K-isomeric state in ^{259}Sg was observed from the reaction with ^{208}Pb targets [4]. The results of this work reveal new insights into the fission properties of the heaviest nuclei and were published in two papers in Physical Review Letters that were both selected as the editor's suggestion.

In the beamtime performed in February-March 2025, the newly constructed focal plane detector (FPD) of the TASCA separator was successfully commissioned. It was used in combination with a Ge detector for the study of various heavy nuclei produced in ^{48}Ca-induced reactions. An attempt to synthesize the hitherto unknown isotope ^{231}Am was performed in the ^{48}Ca+^{nat}Re reaction; the data analysis is ongoing. In May-June 2025, ^{288}Mc and its decay products were produced in the ^{48}Ca+^{243}Am reaction at TASCA and studied with the new ANSWERS setup and unique data on α, α-γ and fission were accumulated and are under evaluation.

Atomic Physics

In 2025 two beamtimes for laser spectroscopy of the heaviest elements took place at SHIP at GSI. In February the JetRIS setup, where laser spectroscopy is performed in an effusing gas-jet, which leads to improved spectral resolution, was successfully used to study ^{254}No. The hyperfine structure of the known 8^- K-isomer, which has a lifetime of only 260 ms, was successfully identified and measured. This enables an identification of the involved nuclear orbitals forming this particular isomer. In June 2025, laser spectroscopy on neutron deficient Cf isotopes was performed with the RADRIS setup. From this we expect to extract the changes in mean square charge radii for an isotopic chain in this element, extending previous results on fermium. Both experiments were performed by an international collaboration with equipment contributions from GSI, HI Mainz and KU Leuven, Belgium. The data is presently under analysis and corresponding articles are in preparation. An article on theory calculations for the atomic level scheme of neutral lawrencium with contributions from HI Mainz was published [5]. An article on results from experimental campaigns on searching for an atomic level in neutral lawrencium, which were performed in 2020 and 2022, was submitted.

The continuing collaboration with the Institute of Physics and the Department of Chemistry at JGU Mainz enabled further measurements of long-lived actinide isotopes with minuscule sample sizes at the RISIKO mass separator in 2025. Here data on long-lived neutron deficient Cm isotopes as well as for ^{250}Cm were recorded, which are currently being analysed. The data analysis of the fermium results was continued and a manuscript on the hyperfine structure in ^{255}Fm, supported by theoretical atomic calculations was submitted.

Chemical Studies

The analysis of the Sg data on the production of $Sg(CO)_6$ acquired at TASCA in 2024 was completed and a manuscript is in the final stages of preparation.

In collaboration with the CTU Prague from FAIR aspirant partner Czech Republic, gas-phase chromatography experiments with gamma-decaying isotopes of Tl (as homolog of Nh) and Po (as homolog of Lv) were performed at NPI CAS Řež (CZ). The studies focused on the interaction of Tl and Po with quartz surfaces in the temperature range of +1000 °C to -170 °C in thermochromatography studies. The radioisotopes were produced in fusion-evaporation reactions using a 48-MeV ^{3}He-beam and recoiled from the thin target into a C catcher foil placed directly behind the target during irradiation. After the end of irradiation, the foil was placed in the chromatography column and heated to release the collected Po or Tl isotopes. Reactive gases, such as oxygen or water vapor could be introduced directly before the chromatography column. The experiments revealed a complex interaction of Tl and Po compounds with the quartz surface, especially under oxidizing conditions. For Po, two – probably oxidised – species were identified in oxygen-atmosphere. The results of the experiments performed in the past years on the interaction of Po and At with differently reactive quartz surfaces were published in 2025 [6][7] and a publication on the results of Po in oxygen-atmosphere has been submitted.

Chemical Theory Supporting Experimental Work

To assist current gas-phase chemistry experiments on the volatility of Po and At, homologues of Lv and Ts, respectively, and to predict the behaviour of those heaviest elements in future experiments, calculations of formation reaction energies and adsorption energies, E_{ads}, of these elements and their compounds on hydroxylated quartz surfaces were performed using relativistic periodic density functional theory implemented in the AMS BAND software.

For group 16 elements, the considered species comprised elements, oxides, hydrides and hydroxides: M, MH_2MO, MO_2 and $M(OH)_2$. It was shown that elemental Po and Lv should be the most volatile of all the considered species over the quartz surface, with E_{ads} of the order of van der Waals bond energies. Hydrides of Po and Lv should be less volatile than the elements with ~20 kJ/mol larger E_{ads} values. Hydroxides, oxides, and, particularly, dioxides, of these elements should be less volatile than the elements, with those of Lv being less volatile than the respective Po compounds [8]. The obtained trend in E_{ads} of the Po compounds is in overall agreement with experimental results.

For group 17 elements, various oxides, hydrides, and (oxy)hydroxides: M, MH, MOH, MO, MOO, OMO, OMOH MO(OH) were considered. It was shown that elemental At and Ts should be the most volatile over the quartz surfaces among all the considered species, with E_{ads} of the order of van der Waals values. Hydride and hydroxide of At and Ts should be slightly less volatile than the elements with ~20 kJ/mol larger E_{ads} values. Oxides and oxyhydroxides of these elements should be the least volatile. All the compounds of Ts should be less volatile than the respective At ones. The differences in the E_{ads} values between the Ts species should also be larger than those between the related At compounds, so that one should be able to differentiate between them more easily.

Technical developments and key contributions to collaborative work

At the SHIPTRAP Penning trap spectroscopy setup, upgrade work was performed in 2025. A compact buffer-gas cell designed for fast and efficient extraction of radionuclides emitted by a recoil ion source was assembled and commissioned. A compact RFQ (Radio Frequency Quadrupole) buncher has been designed to allow coupling the buffer-gas cell to the main beamline of the SHIPTRAP setup [see J. Patel, MSc. thesis, TU Darmstadt (2025)]. The buffer-gas cell and RFQ buncher represent a new ion-source branch providing the SHIPTRAP mass spectrometer with long-lived actinide isotopes of interest for offline high-precision mass measurements. Such heavy nuclides can also be used in online experiments as reference ions allowing real-time monitoring of the magnetic field in the SHIPTRAP solenoid. A publication is in preparation. In May 2025 the SHIPTRAP setup was tested in an online run: the stopping and extraction efficiency of the buffer-gas cell operated at cryogenic temperature was confirmed. A mechanical damage of the main RFQ buncher was identified. This part of the setup is currently under upgrade.

Developments for the laser spectroscopy program included setting up a Multi-Reflection Time-of-Flight (MR-ToF) spectrometer at HI Mainz. It will be connected to a buncher, and will in future extend the capabilities of the group's gas-cell laser spectroscopy program to access longer-lived nuclides, irrespective of their decay mode. The commissioning results from the MR-ToF spectrometer with a preliminary test ion source and the buncher design studies were summarised in [9]. The buncher has been manufactured, assembled and first test measurements have been performed. JetRIS was moved to HI Mainz for further optimization concerning efficiency and towards a coupling with the buncher and the MR-ToF spectrometer, which is foreseen to take place in 2026.

The chemical study of elements beyond Mc requires the development of novel techniques to efficiently transfer short-lived isotopes with half-lives below 100 ms to a gas chromatography detector array. The proposed universal buffer gas stopping cell (UniCell) is based on the radiofrequency (RF) ion-funnel technique and is designed to succeed the TASCA recoil transfer chamber. Ion trajectory and gas-dynamic simulations have been completed and published [10]. Four interfacing printed circuit boards were designed and successfully tested in collaboration with the GSI experiment electronics department to adapt the 350 electrical contacts of the advanced funnel and to provide the required RF signals. The boards were manufactured to match the exact dimensions of the funnel and to improve its overall performance. The main chamber of the setup was designed, manufactured, and assembled. With its successful assembly, the UniCell setup was physically realised, and a first complete version was finalised. Commissioning with short-lived alpha-emitting isotopes is planned to start shortly.

At GSI the renovation of the experimental hall started in July 2025, directly after the successful beamtimes. In this context, major construction changes are addressed in the SHIP cave including a dedicated room with new walls in the basement, the enlargement of escape doors in the cave and the closure of openings between ground floor and the basement. These works include significant construction work in the cave and accordingly a thorough preparation is mandatory before the next on-line beamtime. In parallel to this construction works, the adaptation of the SHIP control system towards the new accelerator control system is required, as some accelerator infrastructure such as the current measurement by trafos was migrated. This needs to happen before the next beamtime in October 2026.

At HI Mainz, the production of tailor-made samples of exotic radionuclides continued to be an important pillar of the SHE Chemistry program. Experiments in the context of the TACTICa collaboration focused on the production and characterization of multiply-charged Th-containing fluoride molecules [11]. Various thorium and uranium samples, including recoil ion sources, laser ablation targets as well as solid state hosts for Th nuclei, tailored for the respective experiments, were produced, characterised and shipped to collaboration partners at KU Leuven, CERN, TU Vienna, and Harvard U. and used in experiments on the "nuclear clock" nucleus ^{229m}Th and related topics; several publications resulted from these and other ongoing collaborations, using samples prepared in the past years [12][13][14]. In collaboration with the University of Greifswald, new insights into actinide-actinide bonds in gas phase were gained. Laser ablation-coupled time-of-flight experiments revealed atomic thorium clusters up to a size of Th_{15}^{+}, showing that for this element, bonds are stronger than in heavier actinides [15]. Various transuranium isotopes including ^{242,243}Cm and ^{249}Bk were produced by neutron irradiation of suitable target isotopes at Institut-Laue-Langevin (ILL, Grenoble, F) and supplied to the laser spectroscopy studies at RISIKO. Targets of the ^{249}Bk and further actinides were produced to enable high-precision mass measurements at the TRIGA-Trap Penning trap setup. Samples of long-lived actinides, which will allow studies of the spontaneous fission process, were prepared for upcoming studies at JRC Geel.

Outlook 2025

For the laser spectroscopy program, in total 60 shifts of main beam were granted for on-line laser spectroscopy measurements by the GSI G-PAC in 2025, which will be scheduled in 2026/27. A parasitic beamtime is planned for October 2026, while the main beamtimes for both, JetRIS and RADRIS, are scheduled for fall 2027. At RISIKO, further measurements on the atomic structure of berkelium are planned for 2026.

Based on the successful experiment with $^{259}Sg(CO)_6$, a SHE Chemistry-led international collaboration has proposed a new experiment on the synthesis and study of properties of Bh carbonyl complexes. The first step, the study of the production cross section of the nuclear reaction ^{208}Pb(^{55}Mn,n)^{262}Bh is scheduled at UNILAC for 2026.

The chemistry studies at NPI CAS Řež will continue to further the understanding of the properties of Po in contact with quartz surfaces and SiC. In addition, experiments with the lighter homolog of Po, i.e., Te, are planned at the NPI CAS Řež and at the TRIGA reactor in Mainz. These will be accompanied by theoretical work on the volatility of Po, a homolog of Lv, yielding predictions of the adsorption behaviour of these elements and their compounds on surfaces and gold and quartz on the basis of the relativistic periodic DFT calculations.

After the successful commissioning of UniCell the next step of the project will focus on the transport of the extracted ions behind the funnel to a chemistry setup and the development of a control system for the setup.

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5. Research of the PANDA Departments

Coordination: Prof. Dr. Klaus Peters (Goethe University Frankfurt & GSI)

5.1 Executive summary

Author: Klaus Peters

The PANDA experiment (see Figure 52) belongs to a new generation of hadron physics experiments, hereby building on the experiences and successes of previous generations. It features a modern multipurpose detector. The combination of a high-quality antiproton beam at the High Energy Storage Ring (HESR), an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. GSI is the PANDA lead laboratory, which coordinates the international efforts of the whole PANDA collaboration (>50 Institutes) to get the detector ready for a rich physics program. This involves overall and technical coordination and integration, core-software and trigger development as well as the full construction of the German in-kind DIRC for PANDA and several individual R&D and construction work packages. This is accompanied by Phase-0 activities involving PANDA hardware like PANDA@HADES, PANDA@MAMI, PANDA@ELSA in Darmstadt, Mainz and Bonn respectively and the new Koala-Experiment planned for Cave C at SIS18 as well as data analysis at GlueX and BESIII at IHEP (Beijing, VR China). To accomplish the goals, the department teams up inside GSI, the sections EMP and SPECF of the Helmholtz Institute Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

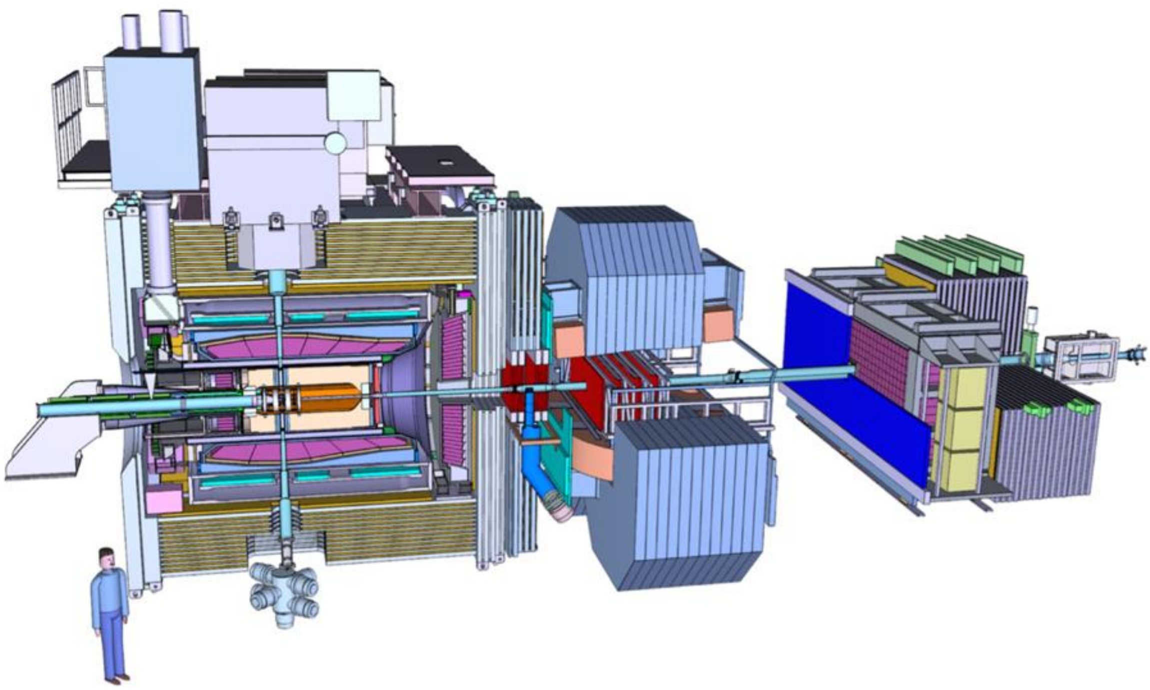

Figure 52: The PANDA Detector (Illustration by J. Lühning, GSI)

5.2 Hadron spectroscopy

Head: Prof. Dr. Klaus Peters (Goethe University Frankfurt & GSI)

Authors: Anastasios Belias, Klaus Götzen, Klaus Peters, Lars Schmitt

Introduction

The PANDA experiment (see Figure 52) belongs to a new generation of hadron physics experiments, hereby building on the experiences and successes of previous generations. It features a modern multipurpose detector. The combination of a high-quality antiproton beam at the High Energy Storage Ring (HESR), an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. GSI is the PANDA lead laboratory, which coordinates the international efforts of the whole PANDA collaboration (>50 Institutes) to get the detector ready for a rich physics program. This involves overall and technical coordination and integration, core-software and trigger development as well as the full construction of the German in-kind DIRC for PANDA and several individual R&D and construction work packages. This is accompanied by Phase-0 activities involving PANDA hardware like PANDA@HADES, PANDA@MAMI, PANDA@ELSA in Darmstadt, Mainz and Bonn respectively and the new Koala-Experiment planned for Cave C at SIS18 as well as data analysis at GlueX and BESIII at IHEP (Beijing, VR China). To accomplish the goals, the department teams up inside GSI, the sections EMP and SPECF of the Helmholtz Institute Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

PANDA Coordination

PANDA Satellites

In 2025 the Excellence Cluster "Color meets Flavor" with 3 participating universities (Bonn, Siegen, Dortmund) and FZ Jülich was approved. In this context Bonn university will receive funding for the INSIGHT experiment at ELSA. Here the PANDA Forward Endcap EMC will be employed as forward calorimeter until PANDA will be installed at FAIR. At GSI further design work on the support structure hosting also the cooling plant and local cable routing continued throughout 2025.

At FZ Jülich at the decommissioned accelerator COSY standalone tests of the PANDA Cluster Jet Target were performed, among others with the newly developed cluster dump and its diagnostic stages. Preparations to implement KOALA at Cave C at GSI continued in 2025. The transfer of the target to GSI is planned for mid 2026. The aim are measurements of elastic scattering of protons in the overlap of the Coulomb domain and the hadronic domain. Measurements at GSI can be set up once the GLAD magnet of R3B was moved to the FAIR High Energy Cave and will be coordinated with the commissioning of the CALIFA and ACTAF systems from NUSTAR in Cave C before also moving to the High Energy Cave (see Figure 53). In this intermediate program also joint physics opportunities in cooperation between PANDA and NUSTAR are in consideration. KOALA will implement tracking of the scattered tracks with pixel detectors. Ongoing preparations for these measurements in Cave C are coordinated together with Münster university, Bochum university and Helmholtz Institute Mainz. Also, in 2025 first planning started to extend the setup in a later phase with further detector systems constructed for PANDA to increase the physics reach of the measurements.

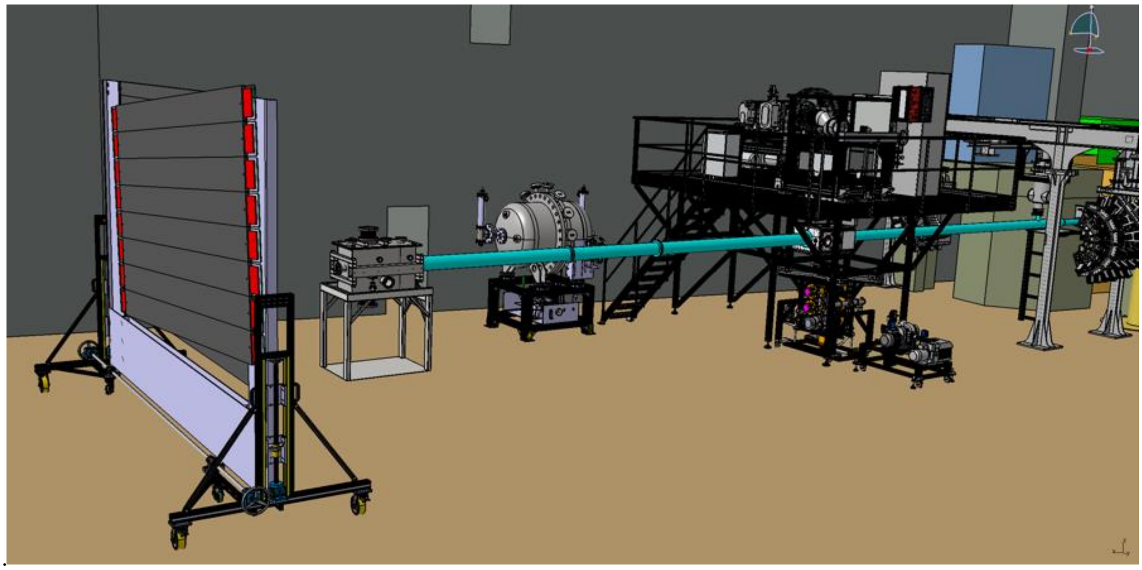

Figure 53: Preliminary setup of Cave C with KOALA, ACTAF and CALIFA.

PANDA Outer Tracker

The LHCb Outer Tracker (OT) which was gifted to GSI for the use at PANDA underwent successful tests in the mCBM setup. A four-plane OT prototype system has been prepared, installed and operated successfully in three beam times, of various particle beams, with the great effort and the help of the DL and EEL departments at GSI. Analyses of the beam time data are in progress. In addition, a task force on the feasibility of using OT straw modules in the CBM MUCH system has been setup up with the preliminary positive conclusion, that it is feasible to use the OT straw modules in the CBM MUCH system to complement the CBM detector and account for delayed components.

The OT modules also triggered the interest of the hadron community at J-PARC. First talks for cooperation with J-PARC have started already, and continued at the international workshop HAMP2025, at J-PARC.

To facilitate the cooperation between FAIR experiments based on already build and readily existing components, parts and systems, a MoU between PANDA and CBM has been signed. The MoU regulates the cooperation of members from both experiments, PANDA and CBM in common projects, while allowing a flexible and dynamic structure as to the subject of each of the projects. The involvement through this MoU allows PANDA members to gain experiences in detector hardware, simulations software and data analyses in the CBM experiment at FAIR.

Software and Analysis

Developments for HepFastSim Software Package

In order to perform simulation studies for various hardware options to explore the possible performance phase space, a ROOT-based stand-alone fast simulation package named *HepFastSim* has been created and developed in 2023/24. This package was continuously improved, and features like the usage of configuration steering variables, storage of arbitrary Lorentz-vector related expressions of particle candidates, list veto filtering, detector parametrization with C++ lambda functions, and more have been added. Furthermore, useful tools for *HepFastSim* job submission to the GSI computing cluster have been provided. With a typical event rate of 3 kHz, the simulation and analysis of about 10^9 events per hour can be achieved by running only 100 jobs in parallel. A comprehensive online documentation was created and published [1]. The package is already used in PANDA related studies and for a master thesis, recently finished at Bochum university. The publication for the full software package under GPLv3 license has been initialised, the GSI-internal process is still ongoing.

qfit – A Versatile Fitting Tools

Performing line shape fits to data spectra is a very common and frequently occurring task in (hadron) physics. The ROOT framework offers many tools to perform these kinds of fits. However, this typically requires the implementation of a significant amount of C++ programming in form of a ROOT macro. This in particular holds when dealing with complicated function models like coherent sums of complex function components, which cannot be expressed as a simple ROOT TFormula. To simplify and, in particular, accelerate this process, the fitting tool *qfit* has been implemented. Given a 1-dimensional graph or histogram, *qfit* out-of-the-box can perform fits with function models consisting of an arbitrary number of individual signal and background components, which are summed up coherently and/or incoherently, choosing out of more the 70 pre-defined functions. It also provides functionality to determine significances, compute fit fractions and plot phases and Argand diagrams. Currently, the tool can be accessed via the GSI internal git server [2].

FAIR Phase-0: Analysis of GlueX Data

The search for the possible exotic resonance φ(2170) in photo production reactions $\gamma p \rightarrow \varphi\pi^+\pi^- p$ in 334/pb of data collected with the GlueX detector in 2017 and 2018 has passed the GlueX internal review process [3]. The differential production cross section $d\sigma/dM_{\varphi\pi\pi}$ has been measured for the first time in photo-production. Two structures are visible in the spectrum and fitted with Breit-Wigner line shapes. One is located at m = 1828 MeV/c^2 with a width Γ= 94 MeV/c^2, the other was fitted with fixed parameters from a previous observation by BESIII in $e^+e^- \rightarrow K^+K^-$ reactions to m = 2.239 MeV/c^2 and Γ= 140 MeV/c^2. The lighter structure could be identified with the known X(18356) or φ_3(1850), while both resonances are not reported yet to decay to $\varphi\pi^+\pi^-$. The observation of the heavier structure around 2.24 GeV/c^2 could be interpreted as a hint for an additional resonance existing in the vicinity of the φ(2170).

FAIR Phase-0: Analysis of BESIII Data

The measurement of the energy-dependent cross-section of the reaction $e^+e^- \rightarrow \eta_c\gamma$ based on data taken by BESIII is progressing, as well as the search for structures in the measured spectrum. The evidence for exotic resonances like the ψ(4230) in the energy dependent cross-section, with a subsequent radiative decay to the charmonium ground state η_c will be an important input to the classification and theoretical understanding of these kind of resonances. The η_c is being reconstructed in 14 different hadronic decay channels at 22 centre-of-mass energies, with signal Monte Carlo already been produced for all the channels and a subset of energies. As a cross check, the J/ψ signals apparent in the mass spectra has been quantified, and the cross section of the reaction $e^+e^- \rightarrow J/\psi\ \gamma_{ISR}$ has been measured and compared with previous publications. In this case the photon does not originate from a radiative decay but is generated by initial state radiation (ISR) before the collision takes place.

Outlook 2026

The PANDA collaboration's long-term goal remains unchanged: science using antiprotons with PANDA in the HESR. As this goal can be achieved at the earliest in 2030s given a decision is taken by the FAIR Council soon, the collaboration is extending the scientific use of already existing equipment at other experiments (PANDA Satellites) and is starting an R&D initiative to update the overall PANDA setup with a focus on modernization and cost-effectiveness, while continuing construction of several detectors(-parts).

Selected publications of 2025

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5.3 PANDA Detectors

Head: Dr. Jochen Schwiening (GSI)

Authors: *: Dr. Roman Dzhygadlo (GSI), Dr. Carsten Schwarz (GSI), Dr. Jochen Schwiening (GSI)*

Introduction

The main objective of the department is the development and construction of an innovative type of Ring Imaging Cherenkov Detector, known as DIRC (Detection of Internally Reflected Cherenkov Light) counter. These compact and robust PID (Particle Identification) detectors use highly polished bars or plates made from synthetic fused silica to generate Cherenkov light and to guide the photons by internal reflection to fast pixelated sensors and readout electronics to determine the velocity of charged particles. The group currently participates in the design, construction, and operation of DIRC detectors in four large experiments: PANDA at FAIR, GlueX at the Thomas Jefferson National Accelerator Facility (TJNAF), USA, ePIC at the future EIC (Electron-Ion Collider) at Brookhaven National Laboratory (BNL), USA, and LHCb at CERN. The group plays key roles in several international detector R&D collaborations and consortia, including EICGenR&D22 at TJNAF, eRD103 at BNL, and DRD4 at CERN.

Highlights & Activities in 2025

The PANDA Barrel DIRC, a German in-kind contribution to FAIR, is designed to provide clean separation between charged pions and kaons for particle momenta up to 3.5 GeV/c. An array of fast and compact micro-channel plate (MCP) PMTs will detect the Cherenkov light. The MCP-PMT signals will be processed by the FPGA-based DiRICH front-end board, developed at GSI. The series production of the MCP-PMTs by Photonis Netherlands BV concluded in 2025 after a total of 106 MCP-PMTs were delivered to GSI. The detailed evaluation at FAU Erlangen [1] found that 63 of those meet the technical requirements, 27 more tubes, provided to PANDA free of charge, will be useful for PANDA or future R&D tests despite failing one or more minor specifications, while 16 MCP-PMTs failed key specifications and were returned to Photonis.

The high-performance DIRC (hpDIRC) for the ePIC experiment at BNL will reuse the legacy DIRC bars from the BaBar experiment at SLAC to reduce the detector costs. The bars were transported from SLAC to TJNAF in 2024 and the refurbishing process started in December 2024. The proposed method for extracting the bars from the aluminium shells, for debonding of the epoxy glue joints using heat guns and traction, and for the cleaning and optical quality assurance of the DIRC bars, successfully passed the EIC (Electron-Ion Collider) project final design review (FDR) in 2025.

The PANDA Detectors department, together with the GSI Hadron Spectroscopy department, Goethe University Frankfurt, Justus Liebig University Gießen, and Bergische Universität Wuppertal, hosted the 12th International Workshop on Ring Imaging Cherenkov Detectors (RICH2025). More than 120 participants from 14 countries met from September 15-19, 2025 at the Erbacher Hof in Mainz to discuss the "state of the art" in Cherenkov light imaging techniques for applications in high energy physics, nuclear physics, and astroparticle physics, as well as novel ideas and future developments in plenary sessions of invited and contributed talks, supported by poster sessions. The proceedings of the workshop will be published in Nuclear Instruments and Methods in Physics Research, Section A.

LHCb TORCH R&D

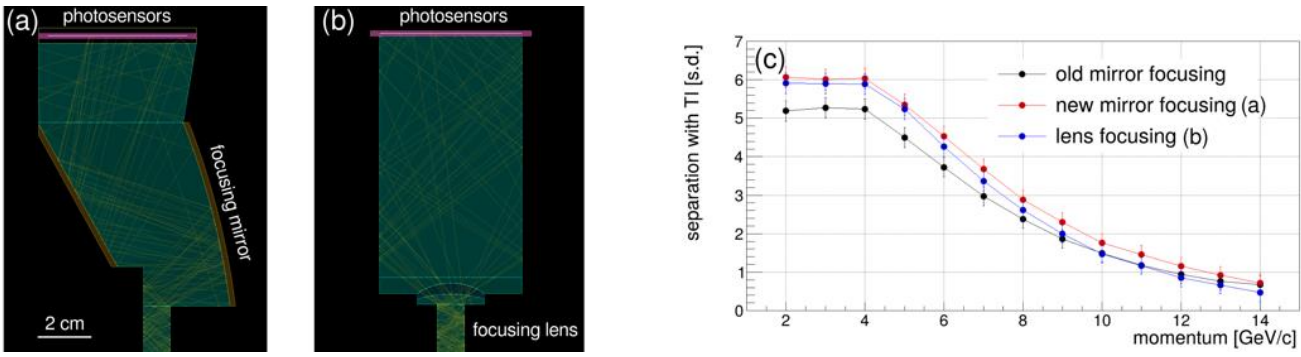

Figure 54: Alternative expansion volume designs for the proposed LHCb TORCH detector with new mirror-based focusing (a) and lens-based focusing (b). The radiator plate is seen in a side view at the bottom, the sensors are located at the top and photon paths are shown in yellow. Performance comparison showing the π/K separation power as a function of particle momentum (c) at a polar angle of 5° using time-imaging reconstruction (TI).

As part of the integration of the TORCH detector into the mechanical structure of the LHCb RICH2 detector, stringent spatial constraints have been imposed, necessitating a redesign of the focusing optics to fit within the available space. Detailed Geant4 simulations were used to develop several more compact focusing designs. Figure 54 shows visualizations of two focusing designs in Geant4 and their π/K separation performance. Compared to the old design, which was based on a single cylindrical mirror, the two-mirror configuration achieves the best performance in the most demanding polar angle range (1°–10°), while the lens-based design maintains excellent performance at larger angles (> 10°).

GSI participated in a comprehensive beam test of a TORCH prototype at the CERN PS in July/August 2025, exposing the full-scale TORCH module to a mixed hadron beam at momenta of 5, 8, and 10 GeV/c. The prototype comprised a highly polished fused silica radiator (250 cm x 66 cm x 1 cm) and a fused silica focusing block in a custom CFRP frame, which is suspended from a rail and serves also as a dark box, and an array of MCP-PMTs read out by NINO and HPTDC boards. The fused silica plate was produced in three pieces, which were bonded together prior to the beam test, following a capillary gluing procedure that was developed 25 years ago for the BaBar DIRC at SLAC and recently optimised for the PANDA Barrel DIRC system by the DIRC groups at HIM Mainz and GSI. A heavyweight support frame for the prototype was developed at the University of Oxford and served as gluing fixture, providing the means to position the optical components with high precision. The alignment of the focusing block and plate segments were controlled using a portable coordinate measuring machine. The support frame and the gluing of the optical components is shown in Figure 55.

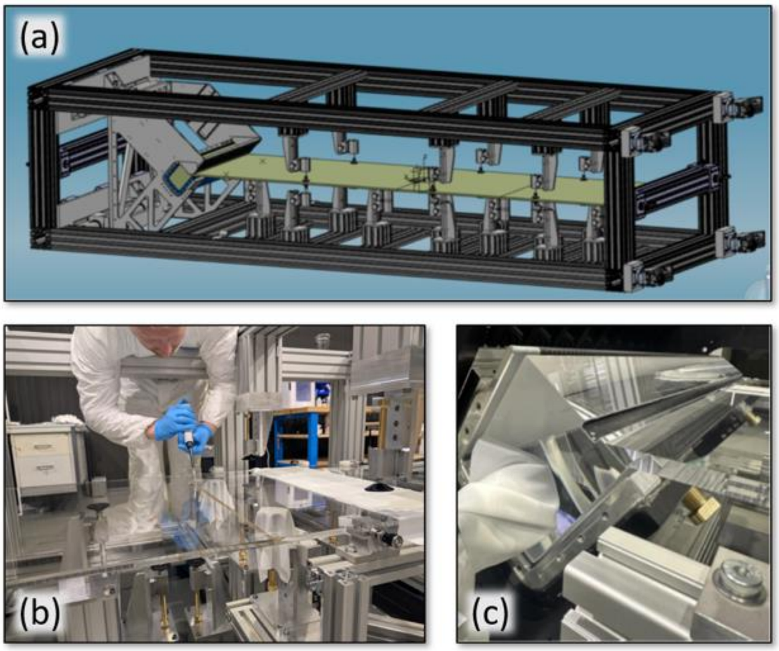

Figure 55: Bonding of the TORCH optical system. CAD drawing of the support frame and bonding jig (a) with the optics highlighted in green. Photos of the gluing process between two plates (b) and of the completed joint between the top plate and the focusing block (c).

During the beam test the prototype was moved vertically to take data at four beam positions along the centre-line of the plates, 5 cm above and below the two plate-to-plate glue joints. The number of detected photons per particle was measured and, using the photon propagation time, separated into two classes: those reflecting off the bottom end of the plate and those propagating directly to the focusing block. The ratio of the two photon categories per beam-entry position is sensitive to the number of glue joints photons encounter. Preliminary analysis of the beam data shows good agreement between the experiment and simulation and revealed no significant loss due to photons traversing multiple bonded optical interfaces, validating the optical quality of the glue joints (Figure 56).

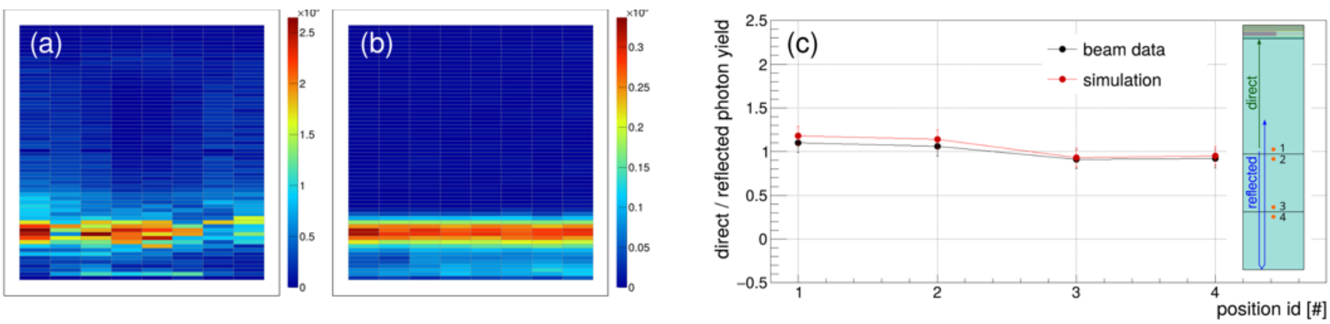

Figure 56: Example of the hit pattern accumulated for a single MCP-PMT for π/p at 5 GeV/c from the beam test (a) and Geant4 simulation (b). Ratio of photon yields per event between photons that go directly to the focusing block and photons that first reflect from the bottom end of the plate (and therefore traverse a larger path length and number of glue joints) for four different positions of the beam impinging on the prototype, as indicated in the insert (c).

The design, assembly, and system-level validation of the first full-scale TORCH module demonstrate significant progress beyond previous small-scale prototypes. The mechanical assembly strategy with lightweight composites and a rail-mounted support, as well the capillary bonding method, have been successfully implemented and tested.

PANDA Barrel DIRC Readout

The modular electronics system for the PANDA Barrel DIRC detector will comprise DiRICH readout, power, and data concentrator cards, all connected to the sensors via one backplane per unit of 4 MCP-PMTs. The thermal management in the compact PANDA detector is challenging. While the readout electronics are the dominant source of heat dissipation, the contribution from the high voltage (HV) dividers for the MCP-PMTs cannot be ignored.

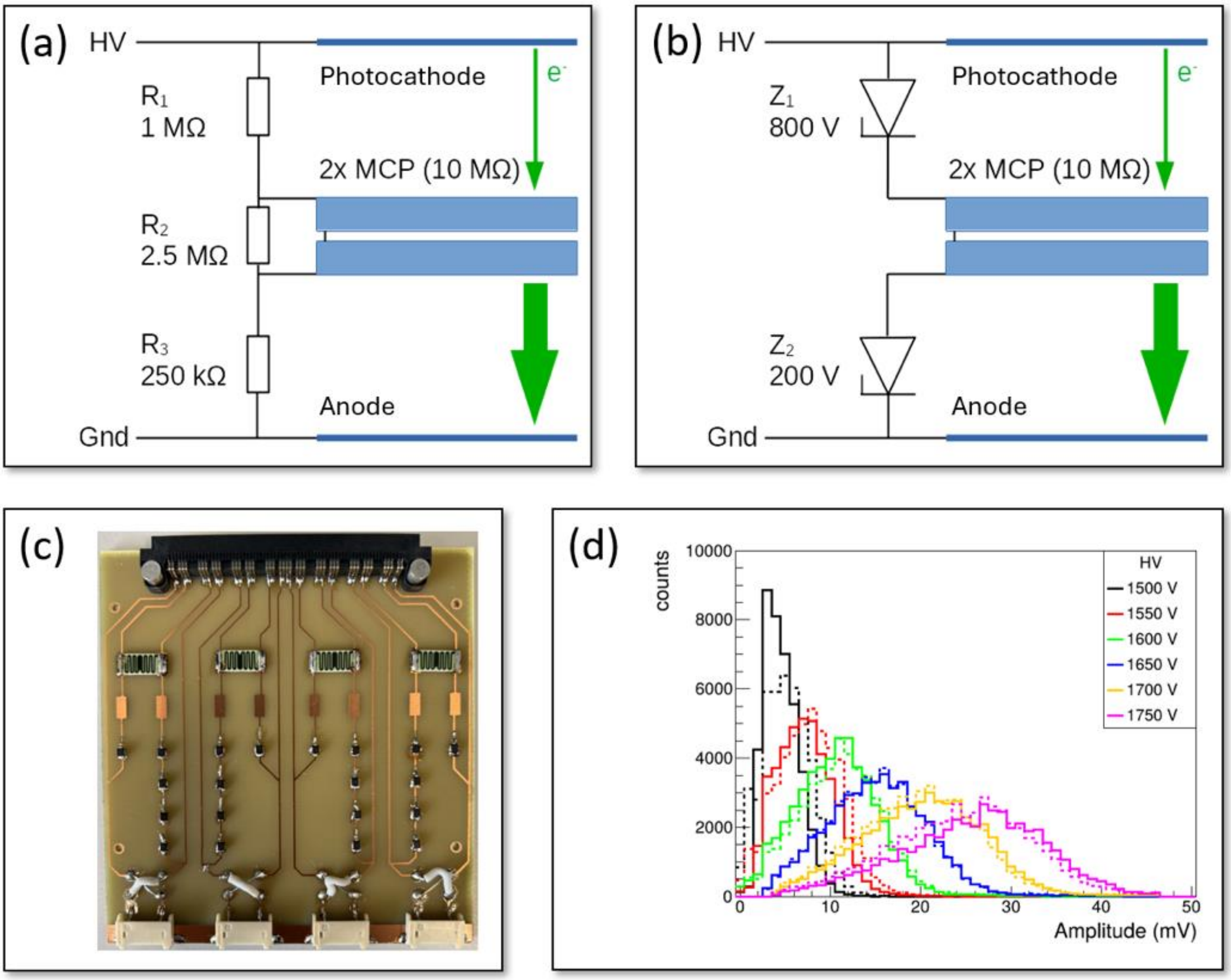

Figure 57: High voltage divider design based on resistors (a) or on Zener diodes (b). Photo of a prototype HV divider board using Zener diodes (c). Measured MCP-PMT amplitude spectra for different HV values (d) for a voltage divider based on Zener diodes (solid lines) and resistors (dashed lines).

To reach the design electron amplification of 10^6, the Planacon MCP-PMTs require high voltages of up to 2000 V between the two MCPs, as well as up to 800 V between the photocathode and the first MCP and 200 V between the second MCP and the anode. In the experiment, these voltages will be supplied by one HV divider per PMT. Typical HV dividers use bleeder resistors to maintain a constant voltage when the detector is operated. For a typical MCP resistance of 10 MΩ and a voltage difference of 2000 Volts over the MCPs, a HV divider with a 4:10:1 ratio, as shown in Figure 57a, results in a power consumption of the bleeder chain of 2.4 W per sensor or about 300 W for the full system. Replacing the resistors R_1 and R_3 with Zener diodes could reduce the power consumption significantly. Figure 57b shows an alternative HV divider design based on two sets of Zener diodes, Z_1 and Z_2. Since not all Zener diode voltages for a specific type are available, several diodes can be used in a sequence to achieve the required voltage regulation with currents as low as 250 μA. A prototype of this board design is shown in Figure 57c. In this example, eight 1PMT4135E3/TR Zener diodes from Microchip Technology are combined in row to replace Z_1. The power consumption is now driven by the current across the MCPs and reduced to 0.4 W for 10 MΩ MCPs. The performance of the two designs is compared in Figure 57d, where the amplitudes of the MCP-PMT pulses are shown for the resistor-based and Zener diode-based designs for different HV values between the two MCPs. The results show a useful application for Zener diodes as replacement for bleeder resistors in high voltage divider for MCP-PMTs, reducing the heat generated by the HV divider by an order of magnitude, simplifying the cooling for the Barrel DIRC readout, and making compressed-air cooling an option.

Outlook 2026

Both the ePIC experiment at BNL and the Upgrade II project for the LHCb experiment at CERN are scheduled to complete their technical design reports in 2026. The group expects to contribute to simulation studies and software development for both projects. The study of new DIRC reconstruction and particle identification techniques, based on machine learning methods, continues, with possible applications in PANDA, as well as GlueX, ePIC, and LHCb. The validation of the mechanical design for the PANDA Barrel DIRC will progress to installation tests in a full-scale a mock-up model at GSI.

Selected publication of 2025

[1] G. Schepers et al., "The PANDA barrel DIRC: From design to assembly," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 1083, p. 171028, 2026, doi: 10.1016/j.nima.2025.171028.

6. FAIR Forschung NRW

Head: Prof. James Ritman (GSI, Ruhr University Bochum & Forschungszentrum Jülich)

6.1 Executive summary

Author: James Ritman

The FAIR Forschung NRW (FFN) Department combines the scientific expertise previously located at Forschungszentrum Jülich, which has now been transferred to GSI. The department maintains strong connections with several universities, including Ruhr-Uni-Bochum, Uni zu Köln, and JGU Mainz, where significant personnel and activities are based. In the field of nuclear and hadronic physics, the department makes significant instrumental and programmatic contributions to the HADES and CBM experiments. Furthermore, expertise acquired in precision physics with polarised beams is being redirected towards precision storage ring measurements at FAIR. The department's neutrino physics activities are making major contributions to the JUNO experiment. The department also pursues several opportunistic activities that complement the main activities already mentioned.

6.2 Hadron-physics studies with HADES

Authors: A. Foda (GSI), D. Grzonka (GSI and FZJ), V. Kladov (RUB and GSI), M. Kohls(GSI), J. Messchendorp (GSI), S. Pattnaik (GSI), G. Perez (RUB and GSI), J. Ritman (GSI, RUB and FZJ), S. Sahu (GSI), J. Taylor (GSI) and P. Wintz (FZJ)

Members of this dept. are extracting hadron-physics observables from exclusively reconstructed reactions in proton-proton and pion-proton collisions. This includes analysing data collected in 2022 with a FAIR Phase0 proton beam of 4.5 GeV and planning upcoming experiments using secondary pion beams.

Highlights of 2025

The analysis of the **elastic proton-proton scattering** process has been completed. This resulted in the extraction of the total integrated luminosity of collected data and the determination of the t-dependence of the cross-section. At the time of the writing up of this report, the corresponding paper draft is undergoing a collaboration-wide review within HADES.

Single-pion production is being investigated through the exclusive reaction $pp \to pn\pi^+$, aiming to extract information on the formation of intermediate Δ and N^* resonances. Using a missing-neutron mass reconstruction technique, a high-statistics dataset has been obtained. The data exhibit a rich spectrum of intermediate N^* and Δ states. These data are being compared to a recently developed coupled-channel framework based on the Jülich–Bonn potential. Preliminary results confirm that the fitting framework using amplitudes derived from the Jülich–Bonn potential, can be systematically applied in a coupled-channel approach. This methodology also be applied to other exclusive pp scattering reactions including those with ηN , $K\Lambda$, and $K\Sigma$ final states.

The analysis of **hidden-strangeness** has been investigated in the reaction $pp \to ppK^+K^-$. First, neural network-based hadron particle identification was finalised, verified with experimental data, and prepared for publication. Other sources of systematic uncertainty were also evaluated, with the largest contribution, up to 10%, arising from efficiency corrections. Differential and total cross section distributions were determined. Additionally, the scattering lengths for nonresonant kaon-proton final-state interactions were determined with high precision. Finally, the measurement of spin-density matrix elements for the $\phi(1020)$ meson was extended to non-diagonal elements, and a preliminary search for the sub-threshold $\Lambda(1405) \to pK^-$production was performed in a coupled channel formalism together with the $\Lambda(1405) \to \Sigma^0\pi^0$ channel.

The **exclusive analysis** of the reaction $p + p \to \Lambda + K_S^0 + p + \pi^+$ showed the presence of dynamics that go beyond a naive incoherent sum of intermediate Δ^{++},$\Sigma^*(1385)$, and $K^*(892)$ contributions. In particular, polarization effects in the vector-meson K^* production has been analysed by extracting the spin density matrix element $\rho_{00} = 0.39$, consistent with no spin-alignment. An analogous study is performed for the Σ^* to search for polarization effects in the hyperon sector. In addition, the Δ^{++} contribution is exploited as an event tag for baryon-resonance decaying to the ΛK_S^0 final state. To further probe baryonic excitations, a dynamical coupled-channel fit from the Jülich-Bonn model will be applied to investigate possible N^* decaying into hyperon–meson final states.

The production of **double strange Ξ^- hyperons** in proton-proton scattering has been studied and a preliminary upper limit of 30 nb at the 95% C.L. is obtained via its decay channel $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$. This result implies that multi-step production must contribute significantly to the excess yield observed in heavy-ion data. The inclusive production of $\Sigma(1385)^-$, which decays into the same final state, is used as a control channel and this reaction is observed with a preliminary cross-section of 5 µb.

This year, preparations for **pion-beam experiments** at HADES have progressed. These experiments exploit the higher cross sections and complementary insights compared to proton- and photo-induced studies. The scientific foundation is outlined in the White Paper "Hadron Physics Opportunities at FAIR" [1] , detailing a decade-long hadron and QCD research program at

GSI/FAIR. The HADES document "π-QCD" [2] specifies the experimental program in preparation for planned beam times. In-depth technical studies were performed to optimize the experimental setup for the planned physics program.

Techniques for **real-time data processing using Machine Learning** (ML) have been extended to further address challenges associated with deploying free-streaming data acquisition systems in future FAIR experiments. A couple neural network-based approaches to predict HADES drift chambers calibration parameters using continuously available environmental data were tested. ML techniques were also used to enhance **particle identification**, specifically by employing Domain-Adversarial Neural Networks. This approach utilised HADES data from both heavy-ion and proton-induced collisions as a benchmark for evaluating performance.

Outlook 2026

- Peer-reviewed publications of elastic proton-proton scattering results and the White Paper outlining the hadron physics opportunities at GSI/FAIR.
- Completion of three PhD dissertations.

6.3 Contributions to the CBM experiment

Authors : F. Goldenbaum (FZJ and BU-Wuppertal), D. Grzonka (GSI and FZJ), S. Gupta (RUB), R. Kliemt (RUB and GSI), J. Messchendorp (GSI), D. Okropiridze (RUB), N. Podgornov (RUB), J. Ritman (GSI, RUB and FZJ), S. Roy (GSI), T. Stockmanns (FZJ), J. Taylor (GSI), P. Wintz (FZJ) and R. Yang (BU-Wuppertal)

Physics program with proton beams

Together with a broad international coalition, members of FFN are spearheading an effort to establish a coordinated, decade-spanning program of hadron and QCD studies anchored at the GSI/FAIR accelerator complex [1]. Profiting from intense deuteron, proton and pion beams coupled with high-rate capable detectors and an international theory effort, the initiative addresses fundamental questions related to the strong interaction featuring confinement and dynamical mass generation. The results of investigations of the physics scope of CBM for this program are presented at the end of this section.

Instrumental contributions

The proposed neutron detector **NCAL** will tag neutrons emitted in a narrow cone around the beam direction at the target. The design of the complete NCAL was finished and the manufacturing of the mechanical components is ongoing. The detector will be a single unit with the NCAL modules placed in a frame of aluminium profiles with lateral dimensions of 1.6 m width and a height of 1.5 m. The NCAL will be positioned behind the FSD detector. The NCAL modules can be arranged in the frame in various configurations adapted to the experimental requirements.

A crucial component of CBM is the Transition Radiation Detector **TRD**, which identifies electrons above 1 GeV/c. The TRD prototype gas system was dismounted in Münster and transported to IKP in Jülich. The set-up of the system in a new laboratory with new installed infrastructure for the gas supply is in progress. Further components needed for the final system, consisting of five parallel pressure-controlled supply lines, were selected and ordered. In addition, work is ongoing to replace the used prototype PLC system with limited capabilities by a more flexible, industrial-grade PLC system with EPICS-based communication for the monitoring and control of the gas circuit operation. A first test system has been set up and presented in a dedicated Gas System Workshop meeting at GSI.

The CBM experiment is a complex detector system composed of numerous subdetectors operating simultaneously and generating thousands of monitoring plots to ensure stable and reliable performance. Given the massive data volumes expected during data taking, continuous verification of data quality and the prompt identification of technical faults are essential. This project proposes the adoption of an AI-based automatic anomaly detection framework, HYDRA, originally developed for the GlueX experiment at Jefferson Lab. HYDRA employs computer-vision models for near–real-time image classification to recognize irregular patterns in detector monitoring outputs. The project focuses on adapting and deploying HYDRA for CBM, including the training and maintenance of dedicated models for individual subdetectors such as STS and MUCH, as well as real-time inference during experimental runs. The implementation of this system will provide an automated and scalable solution to safeguard data quality throughout CBM operations.

Physics simulations

One of the flagship studies for the hadron physics program at CBM is the search for charmed pentaquark states in proton-proton collisions. In preparation to the measurements detailed simulation studies have been performed, employing a model containing three charmed resonances decaying into pJ/ψ (with $J/\psi \rightarrow e^+e^-$) at a beam energy of T=29 GeV. An overall invariant mass resolution for these states of 5-8 MeV/c^2 and a reconstruction efficiency of around 13% can be achieved as well as a reduction of the most prominent background, $pp \rightarrow pp\pi^+\pi^-$, to the same level as the expected signal in the region of interest. With that it is possible to determine the mass and width parameters of the model input through an interfering resonance fit.

Another lighthouse topic to study at CBM is strangeness interactions, which can shed light on the interior of neutron stars. Detailed simulation studies have been performed for the $pp \rightarrow \Lambda\Lambda K^{+}K^{-}$ channel at T=5 GeV. The $\Lambda\Lambda$ invariant mass resolution is determined to be of 6 MeV, indicating a promising possibility to extract scattering lengths from coupled channel cusps.

Quasi-free dp-reaction channels with a proton or neutron spectator have been investigated as part of a feasibility study to reconstruct the Fermi-momentum on an event-wise basis. For proton spectators the performance and required segmentation of the Forward Spectator Detector (FSD) was analysed. For neutron spectators the efficiency and precision of the of the NCAL to measure the momentum determination was studied. The detector performance, event reconstruction and background studies in the full CBM geometry are currently in progress.

Outlook 2026

- The physics potential at CBM with proton and deuteron beams will be further explored and presented as a focus session at the 2026 DPG spring meeting.
- The design of the NCAL system will be finalised and the project will be summarised and presented to the FAIR-ECE as part of the FSD-TDR.
- The prototype of the TRD gas system will be brought into operation at the Forschungszentrum Jülich, where its development will continue.

6.4 Polarised atomic beams

Authors: R. W. Engels (FZJ), N. Faatz (GSI and RWTH), C.S. Kannis (HHU), A. Nass (FZJ), S.J. Pütz (GSI und UzK), and J. Steinhage (FH Aachen)

External electromagnetic fields interact with hyperfine substates leading to a change in occupation numbers used for the build-up of polarization or for its verification. By “optically pumping” HD molecules to a special molecular rotational state with IR Laser, the polarization can be transferred to the nucleus via hyperfine beat [3]. For the SPIN@LHCb project, the former PAX-ABS was transferred, maintained and rebuilt in Ferrara. Beforehand, the high recombination rate in carbon coated storage cells and corresponding molecular nuclear polarization were verified at FZJ [4].

Outlook 2026

The possible production of large amounts of HD molecules by this new type of “optical pumping” might enable the production of polarised fuel for “Polarised Fusion”, i.e., the optimization of future fusion reactors by manipulating the cross sections of the nuclear fusion reactions.

6.5 Precision physics with the JEDI experiment

Authors: A. Andres (FZJ), D. Gu (GSI), V. Hejny (FZJ), A. Kacharava (FZJ), A. Nass (FZJ), J. Pretz (FZJ and RWTH), S. Siddique (GSI)

In 2025 we finalised the analysis of the COSY data concerning the first measurement of the electric dipole moment of deuterons. A paper draft was circulated to the collaboration in 2025. This completes milestone CML-2. The (still preliminary) result is a limit of the deuteron EDM of the order of 10^{-17} ecm. In addition, two PhD thesis are ongoing: one on the design of a combined small electric/magnetic storage ring to measure electric dipole moments of charged hadron by Saad Siddique, and the other one on the possibility of axion searches at the Experimental Storage Ring (ESR) by Daoning Gu. [5][6][7]

Outlook 2026

- Submission of publication on electric dipole measurement of the deuteron.
- Completion of two PhD thesis.
- Investigation of axion search measurements at storage rings.
- Design of a dedicated storage ring for EDM measurements.

6.6 Polarization study in antiproton production

Authors: D. Grzonka (GSI and FZJ), V. Verhoeven (GSI) and H. Xu (GSI)

At the CERN/PS east area a measurement of elastic pbar-p-scattering in the Coulomb-Nuclear Interference region has been performed in order to investigate a possible polarization of antiprotons in the production process. A secondary beam at 3.5 GeV/c was used, and it consisted mostly of pi- and a small fraction of antiprotons. The primary beam and scattered particle were measured with straw tube tracking detectors and scintillating fibres. A 12 cm cell filled with liquid hydrogen was used as the scattering target. Aerogel Cherenkov detectors were used to suppress trigger signals from pions by about a factor 80, resulting in a trigger rate of about 14,000 per spill. The new DOGMA system, developed at GSI, was used for the data acquisition with about 1800 readout channels.

Preliminary analyses show that the rate of produced antiprotons seems to be somewhat lower than expected and the performance of the pion/antiproton separation is also lower than expected, resulting in a reduced precision of the polarization determination. Therefore, another measurement is planned for 2026 at CERN.

Outlook 2026

The analysis of the data taken in 2025 will continue.

A new measurement in 2026 to collect more statistics has been approved by the CERN SPSC. This will use the following detector upgrades:

- Time-of-Flight (TOF), an additional scintillator in the beam line and improved scintillators at the detection system will reach a time resolution of about 100 ps.
- Enhanced PID, the flight path used for the PID will be extended to 19 m. Together with the improved TOF resolution this will enable a robust TOF identification to distinguish pions from antiprotons.

6.7 Electronics and Detector Laboratories

Authors: A. Kononov (GSI), T. Krings (FZJ), T. Sefzick (GSI)

After designing and building interface PCBs for the DOGMA based readout of the various detector components in the P371 test experiment at CERN the FFN Electronics Lab gave on-site support for detector setup and data taking during the beamtime.

The gas system prototype for the CBM TRD has been moved from Münster to Jülich, where a RevolutionPI based EPICS slow control system is currently adapted and connected.

A Compton polarimeter - consisting of a 2D-Si(Li) strip detector followed by a 2D-HPGe strip detector - has been fully completed and was handed over to the SPARC collaboration after successful testing in the laboratory.

In addition, a maskless lithography machine (direct laser writing) has been acquired and commissioned. This machine now enables highly precise (i.e., nanometer-scale) multi-structure processes to be performed on a single detector contact surface.

6.8 Neutrino physics

7.1.1. Authors : L. Ludhova (JGU-Mainz), Z. Che (GSI), M. Malabarba (GSI), Y. Malyshkin (GSI), C. Morales (GSI), M. Rifai (GSI), U. Santhos (GSI), A. Singhal (GSI) and R. Wirth (GSI)

The **Jiangmen Underground Neutrino Observatory (JUNO)** is a 20-kiloton liquid-scintillator detector located 52.5 km from nuclear-reactor cores in China. Its primary goals are the determination of the neutrino mass ordering and the measurement of neutrino oscillation parameters with sub-percent precision, together with a broader neutrino-physics program. JUNO began operation this year, marking its transition from commissioning to its first world-leading measurements of the solar oscillation parameters. During detector filling and commissioning we focused on detector-stability studies and developed an offline data-quality framework that enables continuous assessment of radiopurity and overall detector performance. An intensive calibration campaign established the detector energy response. This included studies of ^{14}C pileup discrimination. A paper describing the detector performance has been submitted for publication [8]. These efforts confirmed that JUNO meets its design performance and is ready for precision neutrino measurements. Using data from the first 59 days of operation, JUNO performed its initial oscillation analysis based on reactor antineutrinos detected via inverse beta decay (IBD). We contributed to event selection, efficiency evaluation and background assessment, including cosmogenic, accidental, muon-induced, and α–n backgrounds, as well as irreducible reactor and geoneutrino contributions. The α–n study builds on earlier work led by our group [9]. We also contributed to spectral fitting and the evaluation of systematic uncertainties. The resulting oscillation contours yield $\sin^2\theta_{12} = 0.3092 \pm 0.0087$ and $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\,eV^2$, corresponding to a 1.6-fold improvement in precision over prior measurements (see Figure 58). These reactor-based results provide an independent test of solar-neutrino oscillation parameters.

The results [10] show that JUNO can reach approximately 20% precision on the total geoneutrino flux in the first years of operation, improving to about 8% over a decade. This work has been submitted to Chinese Physics C [11], and a dedicated geoneutrino data measurement is ongoing.

Borexino, a solar-neutrino experiment located in Italy and the world's most radio-pure liquid-scintillator detector, completed data taking in 2021. Nevertheless, analyses of the full dataset are ongoing. Recently, a new search was performed for high-energy 5.5 MeV solar axions produced in the $p + d \rightarrow {}^3He + A$ reaction [12]. No statistically significant excess above background was observed, and model-independent upper limits were set on the products of the axion coupling constants. These results improve previous experimental sensitivities by approximately a factor of two to three.

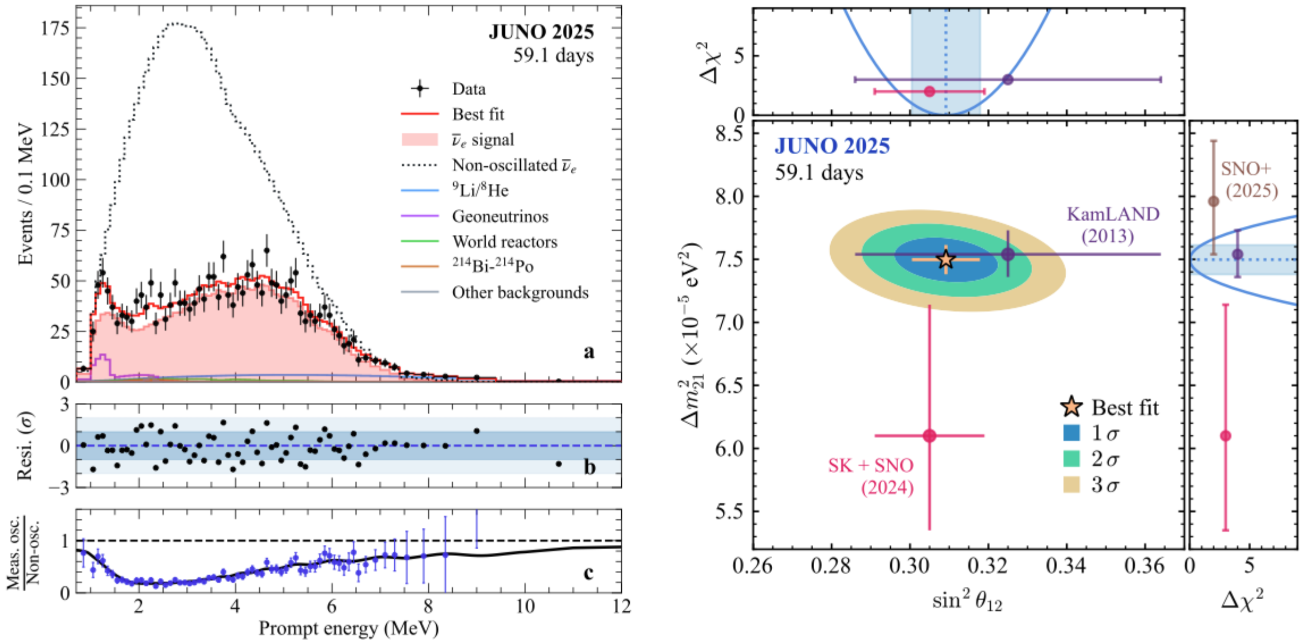

Figure 58: Left: prompt-energy spectrum of inverse beta-decay candidates measured by JUNO, compared with the best-fit oscillation model and background contributions. Right: confidence regions of $\sin^2\theta_{12}$ and Δm^2_{21} obtained from a spectral fit to panel (a), shown together with results from previous reactor and solar neutrino experiments [10].

Highlight FFN publications for 2025

[1] J. G. Messchendorp et al., "Hadron physics opportunities at FAIR." 2026. Available: https://arxiv.org/abs/2512.15986

[2] HADES Collaboration, "π-QCD: Proposal for Experiments at the GSI Pion Beam Facility," GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany, Dec. 2024. Available: https://hades.gsi.de/sites/default/files/web/media/documents/proposals/HADES_Proposal_Pion_Update-1.pdf

[3] C. S. Kannis et al., "Spin manipulation and nuclear polarization enhancement in particle beams with static magnetic fields," Phys. Rev. A, vol. 112, p. 012801, July 2025, doi: 10.1103/4nr6-xt7m.

[4] T. El-Kordy et al., "Tests of amorphous carbon-coated storage cells for a polarized gas target at LHCb and further results*," Chinese Physics C, vol. 49, no. 8, p. 084002, Aug. 2025, doi: 10.1088/1674-1137/add70e.

[5] J. Slim et al., "Proof-of-principle demonstration of a pilot bunch comagnetometer in a stored beam," Phys. Rev. Res., vol. 7, p. 023257, June 2025, doi: 10.1103/PhysRevResearch.7.023257.

[6] V. Hejny et al., "Maintaining a resonance condition of an rf spin rotator through a feedback loop in a storage ring," Phys. Rev. Accel. Beams, vol. 28, p. 062801, June 2025, doi: 10.1103/PhysRevAccelBeams.28.062801.

[7] F. Abusaif et al., "Compact beam position monitor using a segmented toroidal coil," Review of Scientific Instruments, vol. 96, no. 3, p. 033302, Mar. 2025, doi: 10.1063/5.0240076.

[8] A. Abusleme et al., "Initial performance results of the JUNO detector." 2025. Available: https://arxiv.org/abs/2511.14590

[9] J. Collaboration et al., "Simulation of the background from $^{13}C(\alpha, n)^{16}O$ reaction in the JUNO scintillator." 2025. Available: https://arxiv.org/abs/2503.00968

[10] A. Abusleme et al., "First measurement of reactor neutrino oscillations at JUNO." 2025. Available: https://arxiv.org/abs/2511.14593

[11] T. Adam et al., "Prospects for geoneutrino detection with JUNO." 2025. Available: https://arxiv.org/abs/2511.07227

[12] D. Basilico et al., "Search for high energy 5.5 MeV solar axions with the complete Borexino dataset," Eur. Phys. J. C, vol. 85, no. 10, p. 1182, 2025, doi: 10.1140/epjc/s10052-025-14811-9.

7. Research of the Theory Departments

Coordination: Prof. Dr. Hannah Elfner (Goethe University Frankfurt & GSI)

7.1 Executive summary

Authors: Hannah Elfner, Gabriel Martínez-Pinedo

Theoretical calculations are indispensable to gain insights from measurements. On the one hand theoretical predictions allow to test fundamental concepts experimentally. On the other hand, the interpretation of complex measurements is rarely possible without theoretical input. Therefore, the theory groups at GSI work closely together with their experimental colleagues. The 3 departments, namely "Nuclear astrophysics and structure" (Head G. Martínez-Pinedo), "Hadron physics and QCD" (Head M. Lutz) and "Hot and dense QCD matter" (Head H. Elfner) work on microscopic to macroscopic aspects of strongly-interacting matter.

The CRC-TR-211 „Strong-interaction matter under extreme conditions" with H. Elfner being the deputy spokesperson in Frankfurt has been renewed for a third funding period (until summer 2029). Together with colleagues from Darmstadt and Bielefeld theoretical methods to study QCD matter at high temperatures and densities are refined and further developed.

The Helmholtz Academy for Research at FAIR (HFHF) has been evaluated as being excellent in Fall 2025, M. Bleicher and G. Martínez-Pinedo are directors of the academy.

Several members of GSI theory (Andreas Flörs, Almudena Arcones, Andreas Bauswein, and Gabriel Martínez-Pinedo) organised the Hirschegg workshop "Nucleosynthesis of Heavy Elements: r-process". The workshop brought together 53 participants, including 12 female researchers and 19 early career scientists, fostering a diverse and collaborative environment. In April 2025, the biggest conference in the field of relativistic heavy-ion collisions "Quark Matter 2025" took place in Frankfurt. Many members of GSI theory (M. Bleicher, H. Elfner, J. Steinheimer and Elena Bratkovskaya) were part of the local organizing committee, responsible for the student day and an excursion to GSI/FAIR. The international colleagues were impressed with the state of the developments and the new research infrastructures. H. Elfner was also invited to present the Theory summary talk of the conference. In June 2025, the most important conference in the field of nuclear astrophysics, Nuclei in the Cosmos, took place in Girona, Spain. Gabriel Martínez-Pinedo and Friedel Thielemann were members of the International Advisory Committee. Invited speakers included Almudena Arcones, Andreas Bauswein and Andreas Flörs from GSI Theory. Gabriel Martínez-Pinedo was asked to provide the final summary of the conference. Hannah Elfner was a member of the International Advisory Committee of INPC 2025 and Initial Stages 2025.

Jan Steinheimer-Froschauer has become the convener of the DIG-UM Topic Group 'Big Data Analytics'. The white paper on QCD opportunities at GSI/FAIR has been finalised with major contributions from several members of the GSI theory departments. Several members of the Nuclear Astrophysics and Structure department have joined the Einstein Telescope collaboration and contributed to the Blue Book "The Science of the Einstein Telescope".

7.2 Hot and dense QCD matter

Head: Prof. Dr. Hannah Elfner (Goethe University Frankfurt & GSI)

Authors: Hannah Elfner, Elena Bratkovskaya, Jan Steinheimer-Froschauer

Introduction

The main goal of the theory groups working on hot and dense QCD matter is to understand the dynamical evolution of heavy-ion collisions over a broad range of beam energies. For the interpretation and prediction of experimental measurements, it is crucial to provide detailed calculations that connect observables to input from quantum chromodynamics. Together with colleagues in Europe and international collaborators, sophisticated calculations based on relativistic hydrodynamics and transport theory are performed. Several transport approaches are continuously developed and applied by experimental collaborations and theory colleagues from all over the world. In 2025, major efforts went into flexible treatments of nuclear potentials, the extraction of transport coefficients and the exploration of electromagnetic probes. In addition, the isospin asymmetry in kaon yields measurements is explained by adjustments in the fragmentation function.

Highlights in 2025

In recent years many new experimental data that can be used to constrain the dense equation of state of nuclear and QCD matter have become available. This includes high statistics measurements of heavy ion collisions the HADES (SIS18) and STAR (RHIC) experiments and new observations of binary neutron star mergers and neutron star mass-radius relations. In 2025 we have extended the UrQMD (Ultra-Relativistic Quantum Molecular Dynamics) model to incorporate a state-of-the-art chiral mean field model (CMF) based equation of state of dense QCD matter. This is done by introducing the CMF-calculated, momentum dependent, potentials to the QMD part of UrQMD.

In a recent publication [1] we have shown the ability of this new UrQMD-CMF model to simultaneously describe data from heavy ion reactions at the HADES experiment and give a satisfactory description of neutron star mass radius relations based on a single set of EoS-model parameters. The observables in heavy ion reactions included elliptic and directed flow of protons as well particle multiplicities of pions and strange hadrons all which are in good agreement with HADES data (as shown in Figure 59). Our work serves as an important step towards such future studies where the properties of dense QCD matter, through parameters of the CMF model, can be constraint using a comparison of the UrQMD model with high precision heavy ion data, finally also allowing direct comparisons with neutron star and neutron star merger observables.

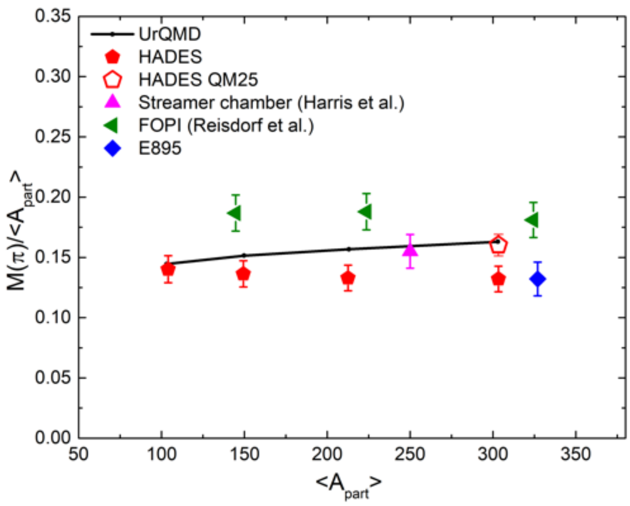

Figure 59: *Centrality dependence of the pion multiplicity from UrQMD-CMF, scaled to the number of participants compared with world data.*

In addition to the equation of state the transport coefficients encode the properties of hot and dense strongly-interacting matter. The STAR collaboration has finalised the Beam energy scan program at the Relativistic Heavy Ion Collider (RHIC) and released a wealth of experimental data. We have applied our viscous hydrodynamics plus hadronic transport hybrid approach (SMASH+vHLLE hybrid; https://github.com/smash-transport/smash-vhlle-hybrid) to extract the temperature and density dependence of the transport coefficients of the produced matter [2]. The shear viscosity (see Figure 60) measures the resistance towards sidewards movement, while the bulk viscosity counteracts expansion of the system. The temperature dependence of transport coefficients has been constrained from high energy heavy-ion collisions. Moving downwards in beam energy towards the FAIR-CBM energy regime the net baryon chemical potential dependence is important. At this point, there are not very strict constraints on the density dependence based on the current experimental data from the RHIC beam energy scan. The results of analysing a large data set with Bayesian analysis techniques are shown below. The comparison to other substances in nature suggests a rather perfect liquid.

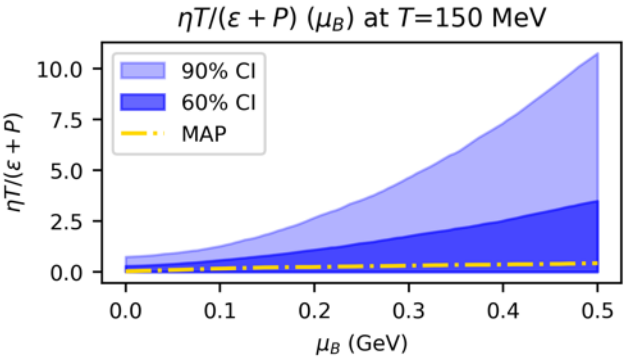

Figure 60: Shear viscosity as a function of net baryon chemical potential. The 60% and 90% confidence intervals are indicated by dark/light blue bands as extracted from the Bayesian analysis.

Electromagnetic probes, such as dileptons, provide information about the properties of the strongly interacting hadronic and partonic matter created in heavy-ion collisions. Since they are undisturbed by the strong final state interaction, they are emitted during the whole evolution of the expanding system from many different sources - from hadron decays to QGP thermal radiation - such that the consistent description of dilepton production requires an application of dynamical models. In Ref. [3] we have investigated dilepton production in heavy-ion, proton-proton, and proton-nucleus collisions from low energies of 1 AGeV (SIS) to ultrarelativistic energies (LHC) using the parton-hadron-string dynamics (PHSD) transport approach. Key dilepton sources in PHSD include hadronic decays, bremsstrahlung, QGP radiation ($q+\bar{q}\to e^+e^-$, $q+\bar{q}\to g+e^+e^-$, $q+g\to q+e^+e^-$), primary Drell-Yan (DY) production (contribution grows with decreasing collision energy), and semileptonic decays of correlated charm and bottom pairs (contribution decreases with lowering collision energy). We have investigated the influence of the QGP EoS with an explicit μ_B dependence based on lQCD - interpreted in terms of properties of quasiparticles and their interactions within the effective DQPM model - on dilepton production. Our study of the excitation function of QGP dileptons, including the μ_B-dependent quasiparticle masses and widths, compared to correlated charm and Drell-Yan, shows that the QGP radiation overshines charm and DY contributions at s≃25−30 GeV in central Au+Au collisions, providing access to thermal QGP dileptons at BES RHIC and future FAIR SIS 300. We have provided predictions for the dilepton spectra for FAIR experiments and shown that at FAIR SIS100 energies the in-medium hadronic contributions will continue to be dominant in the low-mass dilepton region, but a sizable partonic component may emerge in the intermediate-mass range. These findings highlight the potential of SIS100 to explore the parton-hadron transition at high net-baryon density after careful estimation of Drell-Yan contribution by measurement in pp collisions (see Figure 61 for one example).

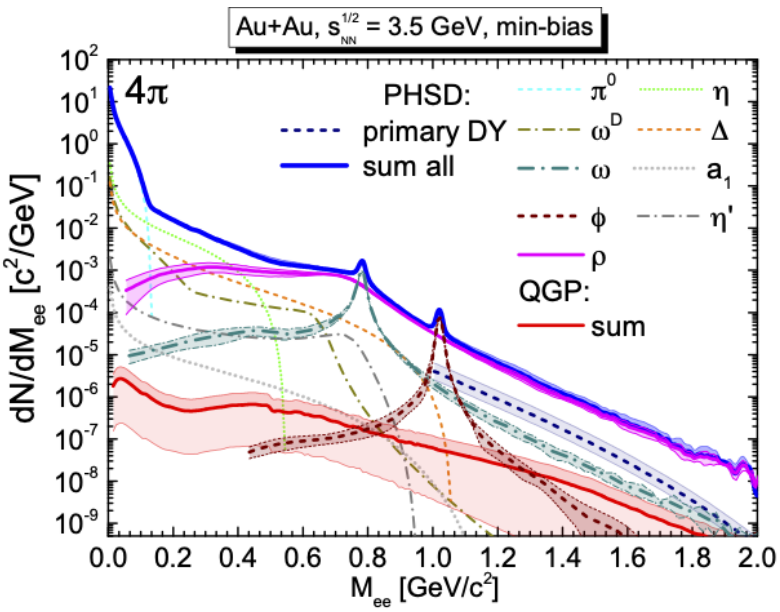

Figure 61: Invariant mass spectra of dileptons from PHSD for minimal bias Au+Au at $\sqrt{s_{NN}}$ = 3.5 GeV.

It was also shown that these fluctuations are not observed in a fixed momentum space acceptance used in experiments. As light nuclei formation may be sensitive to the coordinate space fluctuations, we also estimated the production yield of light nuclei within the UrQMD model. It was observed that while the fluctuations during the phase separation are large also the light nuclei yield is increased. However, that yield decreases again as the system approaches its freezeout. Even though we did not observe a significant signal, our study, for the first time, showed that enhancements of the fluctuations of the baryon number will appear even in such short-lived systems as created in heavy ion reactions.

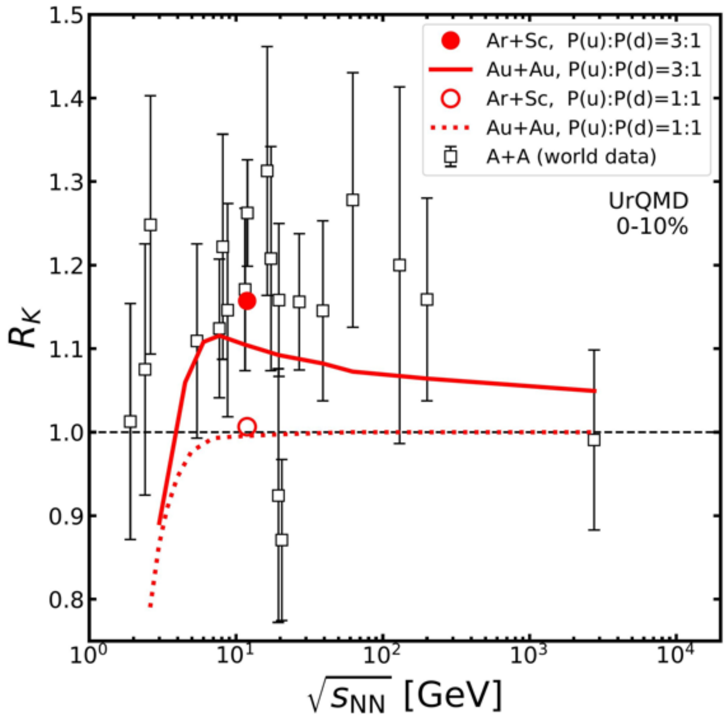

Figure 62: Beam energy dependence of the charged to neutral kaon multiplicity radius for Au+Au collisions. The UrQMD results with modified string fragmentation (solid line) is compared to the default version (dashed line).

Outlook 2026

With a working model which allows to implement a wide range of density and momentum dependent equations of state, based consistently on a chiral mean field Lagrangian, we can now study effects of the equation of state of dense QCD matter and a phase transition in a state-of-the-art transport approach. As a complementary approach the SMASH-vHLLE hybrid approach is extended to lower beam energies by dynamically coupling the transport and the hydrodynamic evolution. This allows for studying the effect of a phase transition on observables. In addition, we plan to study the effect of the hyperon interaction in dense matter on hyperon flow observables which may give direct constraints on the relevance of hyperons in neutron stars and dense QCD matter. Furthermore, we plan to extend our predictions for charm production at the SIS300 to p+Au collisions up to 30 A.GeV beam energy as well as study the asymmetry in kaon production in that system which will become available in the CBM experiment (see Figure 62). In 2026 we plan to extend our study on the influence of EoS on dilepton production by exploring the EoS with critical point and possible phase transition from hadronic to partonic medium focusing on FAIR energies.

Selected publications of 2025

[1] J. Steinheimer, M. Omana Kuttan, T. Reichert, Y. Nara, and M. Bleicher, “Simultaneous description of high density QCD matter in heavy ion collisions and neutron star observations,” *Phys. Lett. B*, vol. 867, p. 139605, 2025, doi: 10.1016/j.physletb.2025.139605.

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[3] A. W. R. Jorge, T. Song, Q. Zhou, and E. Bratkovskaya, “Electromagnetic emission from strongly interacting hadronic and partonic matter created in heavy-ion collisions,” *Phys. Rev. C*, vol. 111, no. 6, p. 064904, 2025, doi: 10.1103/PhysRevC.111.064904.

[4] T. Reichert, J. Steinheimer, and M. Bleicher, “Explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions,” *Phys. Lett. B*, vol. 873, p. 140170, 2026, doi: 10.1016/j.physletb.2026.140170.

7.3 Nuclear astrophysics and structure

Head: Prof. Dr. Gabriel Martínez-Pinedo (Technical University Darmstadt & GSI)

Authors: Andreas Bauswein and Gabriel Martínez-Pinedo

Introduction

The goal of the theory groups working on Nuclear Astrophysics and Structure is to combine advances in the microscopic description of nuclear processes with state-of-the-art astrophysical simulations to improve our understanding of the evolution of stars, the nucleosynthesis of elements in the Universe and the observational signatures of the high-density equation of state and element formation.

Highlights in 2025

A comprehensive description of r-process nucleosynthesis in neutron star mergers requires simulations that account for all mass ejection channels, nuclear network calculations and radiative transfer modelling to generate synthetic kilonova light curves and spectra, which can be compared to observations. These observations include both electromagnetic and gravitational wave signals.

Within a collaborative effort, we investigated features of tungsten in the late time kilonova emission [1]. This work is based on updated data for the electron-impact excitation effective collision strengths, which allows to relate a specific strength of a tungsten emission feature to the abundance of this element in the outflow. This bears potential to constrain the abundances of other elements as well by exploiting correlations of the tungsten abundance with the yields of for instance heavy r-process elements.

We have explored the appearance of Actinide signatures in neutron-rich ejecta from neutron star mergers. Our non-local thermodynamic equilibrium models account for the radiative power produced by the alpha decay of long-lived actinides. The resulting kilonova spectra models suggest that doubly ionised Ac and Th may be particularly interesting as spectral indicators of actinide presence in KN ejecta [2]. A systematic method based on Bayesian techniques to optimize atomic structure calculations of opacities for kilonova modelling. The method has been applied to calculations using the Flexible Atomic code but can be easily extended to any other code [3].

We have connected nucleosynthesis results to observations and galactic chemical evolution. We provided yields from 189 neutrino-driven core-collapse supernova (CCSN) simulations covering zero-age main sequence masses between 11 and 75 $M_\odot$ and three different metallicities and use the yields as input in a GCE model of the Milky Way [4] . We conclude that at least half of the massive stars have to explode to match the observed abundance ratios. If the explosions are too energetic, the high amount of iron will suppress the abundance ratios. With this, we demonstrate how GCE models can be used to constrain the evolution and death of massive stars. We investigated the r-process astrophysical conditions following a site-independent approach based on three key parameters: electron fraction, entropy, and expansion timescale [5]. Our results show that a wide range of conditions produce very similar abundance patterns explaining the observed robustness of the r-process between the second and third peak. Furthermore, we cannot find a single condition that produces the full solar r-process pattern from first to third peak. Instead, a superposition of at least two or three conditions or components is required to reproduce the typical r-process pattern as observed in the solar system and very old stars.

We published a study on using machine learning techniques for gravitational-wave data analysis [6]. This work is targeted at future detections of the postmerger gravitational-wave emission of neutron star binary mergers. Although only a proof of principle, the study shows a promising performance of identifying the main features of the signal. We accomplished a comprehensive study on the specific impact of hyperons on neutron star mergers [7]. This work addresses the gravitational-wave emission, mass ejection, thermodynamical properties and the formation of black holes in the aftermath of the merger. All those aspects are found to be influenced by the presence of hyperons in neutron star matter offering the possibility to learn about hyperonic degrees of freedom in high-density matter. We conducted a systematic investigation of the impact of the hadron-quark phase transition on the gravitational-wave emission of neutron star mergers quantifying for the first time for which range of phase transition properties signatures of the transition would become apparent in a future gravitational wave measurement [8].

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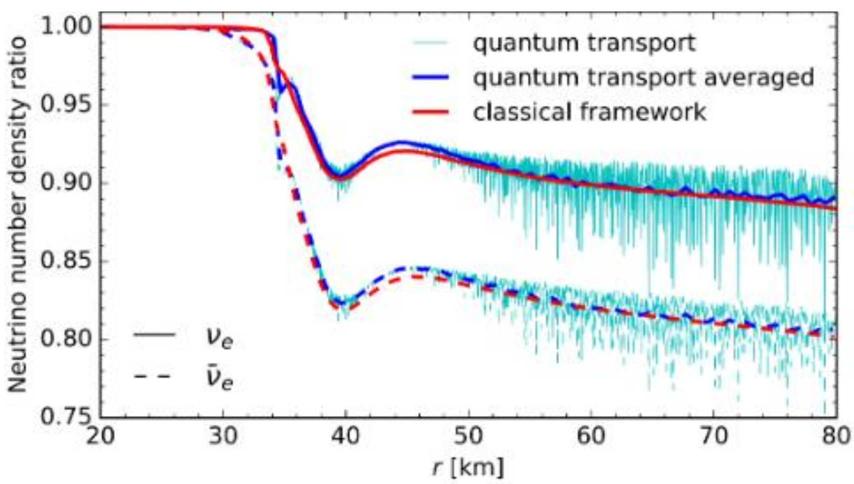

Figure 63: *Radial profiles of neutrino number density ratios comparing results of a fully quantum transport scheme with a classical transport scheme that incorporates novel analytical prescriptions.*

In collaboration with Meng-Ru Wu and his group at the Academia Sinica (Taiwan), we explored efficient approximate methods to include fast neutrino flavour oscillations in supernova simulations. Despite the huge disparity of involved scales for oscillations and collisions, we demonstrate excellent agreement between results adopting effective descriptions of oscillations and direct solutions of neutrino quantum kinetics. Our work highlights that robust integration of neutrino flavour oscillations in simulations can be feasible [9] (see Figure 63). The conditions for the fast flavour oscillations have been searched in supernova explosions in which a transition to a quark-gluon plasma takes place, and the potential effects on the nucleosynthesis and neutrino signals have been estimated [10] .

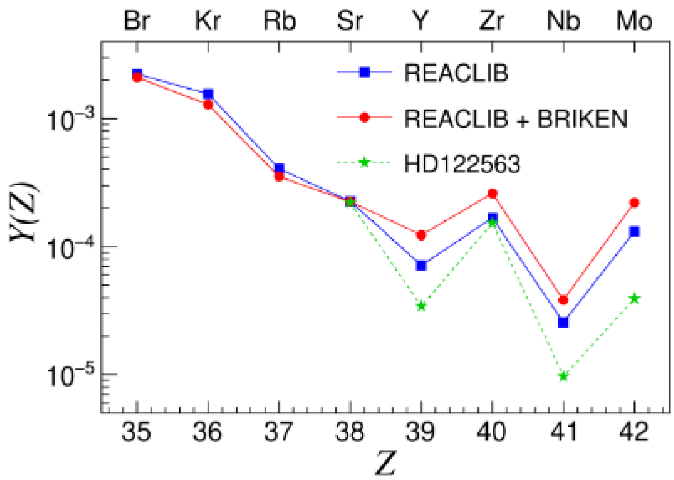

Figure 64: Impact of newly measured beta-delayed neutron emission probabilities on the production of selected elements.

In collaboration with the FRD/SFRS experiments department, we have explored the impact of new mass measurements for neutron-rich tin isotopes beyond N=82. These measurements enhance our understanding of the nuclear structure and astrophysical nucleosynthesis in this previously unexplored region and allow for an improved evaluation of the final abundances of nuclei with mass numbers A=135 and 137 in r-process [11]. We explored the impact of newly measured neutron emission probabilities and half-lives of 37 β-delayed neutron emitters from ^{75}Ni to ^{92}Br at RIKEN [12]. These nuclei lie in the path of the weak r process occurring in neutrino-driven winds from the accretion disk formed after the merger of two neutron stars synthesizing elements in the A~80 abundance peak. We performed abundance calculations based on over 17 000 simulated trajectories describing the evolution of matter properties in the merger outflows and showed that the new data lead to an increase of 50%-70% in the abundance of Y, Zr, Nb, and Mo (see Figure 64). These results underline the importance of including experimental decay data for very neutron-rich β-delayed neutron emitters into r-process models.

We studied measures of multi-particle entanglement and quantum complexity in the ground state of nuclei, and found that these quantities, in particular multi-proton-neutron entanglement, clearly capture information about deformation and, more generally, shape collectivity. This confirms the long-thought role of the interplay between protons and neutrons in driving collectivity and the shapes of nuclei [13].

The MultiGrav project funded from the Innovations pool of the research field Matter started its activities aimed to conduct cross-topic research in multi-messenger physics with gravitational waves.

Outlook 2026

We plan to perform long-term radiation hydrodynamical simulations that follow the dynamics of the ejecta up to times for which the expansion becomes homologous. This will provide a complete description of the thermodynamical history of the ejected matter for nucleosynthesis studies. Those studies will be supplemented with radiative transfer simulations using a complete database of atomic opacities to connect the properties of the ejected matter and nucleosynthesis yields with kilonova spectra.

Selected publications of 2025

[1] M. McCann et al., "Luminosity predictions for the first three ionization stages of W, Pt, and Au to probe potential sources of emission in kilonova," Monthly Notices of the Royal Astronomical Society, vol. 538, no. 1, pp. 537–552, Mar. 2025, doi: 10.1093/mnras/staf283.

[2] Q. Pognan et al., "Actinide signatures in low electron fraction kilonova ejecta," Monthly Notices of the Royal Astronomical Society, vol. 536, no. 3, pp. 2973–2992, Jan. 2025, doi: 10.1093/mnras/stae2778.

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[4] F. P. Jost, M. Molero, G. Navó, A. Arcones, M. Obergaulinger, and F. Matteucci, "Neutrino-driven core-collapse supernova yields in Galactic chemical evolution," vol. 536, no. 3, pp. 2135–2148, Jan. 2025, doi: 10.1093/mnras/stae2718.

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[6] T. Soultanis, K. Maltsev, A. Bauswein, K. Chatziioannou, F. K. Röpke, and N. Stergioulas, "Gravitational-wave model for neutron star merger remnants with supervised learning," Phys. Rev. D, vol. 111, p. 023002, Jan. 2025, doi: 10.1103/PhysRevD.111.023002.

[7] H. Kochankovski, G. Lioutas, S. Blacker, A. Bauswein, A. Ramos, and L. Tolos, "Impact of hyperons on neutron star mergers: Gravitational waves, mass ejection, and black hole formation," Phys. Rev. D, vol. 112, p. 023014, July 2025, doi: 10.1103/vrnr-lf6k.

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[9] Z. Xiong, M.-R. Wu, M. George, and C.-Y. Lin, "Robust integration of fast flavor conversions in classical neutrino transport," Phys. Rev. Lett., vol. 134, p. 051003, Feb. 2025, doi: 10.1103/PhysRevLett.134.051003.

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[11] A. Mollaebrahimi et al., "Precision mass measurements reveal low neutron pairing in tin beyond $N = 82$ and its impact on stellar nucleosynthesis," Phys. Rev. Lett., vol. 134, p. 232701, June 2025, doi: 10.1103/ctyj-ls15.

[12] A. Tolosa-Delgado et al., "Impact of newly measured β-delayed neutron emitters around $^{78}\mathrm{Ni}$ on light element nucleosynthesis in the neutrino wind following a neutron star merger," Phys. Rev. Lett., vol. 134, p. 172701, May 2025, doi: 10.1103/PhysRevLett.134.172701.

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8. Collaborations & Cooperations

8.1 Helmholtz Research Academy HESSE for FAIR (HFHF)

Head: Prof. Dr. Thomas Aumann (Technical University Darmstadt & GSI)

Author: Priv.-Doz. Dr. habil. Frank Nerling (GSI & Goethe University Frankfurt)

Introduction

The Helmholtz Research Academy Hesse for FAIR (HFHF) has been established for fundamental research to improve our understanding of the universe. It is dedicated to foster experimental and theoretical research in the context of the upcoming FAIR facility at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. The research academy serves and combines five institutions in Hesse, namely the Goethe University Frankfurt (GUF), the Frankfurt Institute for Advanced Studies (FIAS), the Technical University Darmstadt (TUDa), the Justus-Liebig University Giessen (JLUG), and the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (GSI). It has been founded and started beginning of 2020.

In total more than 50 professors and principal investigators from these five institutions are brought together by the academy in order to perform excellent research in a collaborative way, making use of strong synergies between the partners. The research funded by HFHF makes especially use of and is related to the upcoming FAIR accelerator facility at GSI. Particles and heavy ions such as antiprotons, gold and lead ions can be accelerated to nearly the speed of light.

The HFHF research program includes moreover applied research, for which the accelerated particles and ions will be used to develop new materials and to further develop proven cancer therapies. The research program of the research academy consists of basically five main research topics, namely
- Physics of hot and dense matter (CBM): Experiment and Theory
- Hadron physics (PANDA): Experiment and Theory
- Nuclear structure physics and nuclear astrophysics (NuSTAR): Experiment and Theory
- Atomics, plasma and applied physics (APPA): Experiment
- Accelerator physics and scientific computing

In total eight program directors elected by the principal investigators for the given research area build the HFHF board of directors that is chaired by the managing director and his deputy. They are supported by the central coordination and administration office. In addition, there is a council of the academy, in which each of the partner institutions is represented. The council is accompanied by the external program advisory board.

Highlights in 2025

An important milestone in 2025 was the evaluation of HFHF that took place at GSI Darmstadt at the beginning of October. During a couple of days, we have been reviewed and evaluated by an international outstanding review committee chaired by Prof. Reiner Krücken (LBNL, Berkeley). The dense program comprised a session of reports given by the HFHF Program Directors for the eight different program areas as well as an overview report by the managing director, whereas sufficient time for questions and discussions by and with the reviewers has been ensured. Moreover, a poster session mainly presented by Early Career Scientists has been organised. A common dinner of the reviewers, the GSI Scientific director, the Board of Directors and the Academic Council of HFHF took place, providing a cosy opportunity for further (informal) exchange. Finally, a guided visiting tour to the FAIR construction site completed the hospitality for our international review panel. The review was about the HFHF achievements for the years 2021-25 as well as the potential for future scientific and technical excellence of HFHF, and HFHF's relevance for the completion and the success of FAIR. The final outcome as summarised in a corresponding report was very positive.

Further to be mentioned is the organization of the 4th workshop [*] of a series of events within the newly established initiative "QCDatFAIR" for developing a new cross-community strong QCD-driven hadron physics program. A vital aspect of this initiative is maintaining a coherent collaboration that integrates expertise from both, theoretical and experimental communities. This recent workshop was organised to complete the write-up of the outcome of the discussions among the about hundred experts of the field involved, ensuring broad consensus on the contents. This White Paper titled "Hadron Physics Opportunities at FAIR" foreseen to be published in the peer-reviewed journal "Progress in Particle and Nuclear Physics" is meanwhile available on the preprint server: http://arxiv.org/abs/2512.159868.

[*] EMMI Collaboration Meeting: QCD at FAIR Workshop 2025: *"QCD at FAIR – A cross-community driven hadron-physics program at GSI/FAIR"* Organizers: Frank Nerling, Johan Messchendorp and Jim Ritman, together with Alessandro Pilloni and Isaac Vidana (LOC), Catania, Sicily, Italy, June 22nd – 27th, 2025, for details see: https://indico.gsi.de/event/21757/

HFHF events in 2025 (organised or supported by HFHF)

- "Quark Matter 2025" - 31st International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Organizers: D. Rischke (chair), T. Galatyuk (co-chair) et al., April 06th – 12th, 2025, Frankfurt am Main, Germany
- "INPC 2025" - International Nuclear Physics Conference, H. Elfner (Intern. Advisory Committee), May 25th – 30th, 2025, Daejeon, Republic of Korea
- EMMI Collaboration Meeting: QCD at FAIR Workshop 2025: "QCD at FAIR – A cross-community driven hadron-physics program at GSI/FAIR", Organizers: F. Nerling (chair), J. Messchendorp (co-chair, J. Ritman, June 22nd – 27th, 2025, Catania, Sicily, Italy
- "Initial stage 2025" - The 8th International Conference on the Initial Stages of High-Energy Nuclear Collisions, H. Elfner (Intern. Advisory Committee), September 07th – 12th, 2025, Taipei, Taiwan
- "RICH 2025" - The 12th international workshop on Ring Imaging Cherenkov Detectors, Organizers: Claudia Höhne, Klaus Peters, September 15th – 19th, 2025, Mainz, Germany
- "International School of nuclear physics", 46th Course, Organizers: C. Fischer, T. Galatyuk, September 17th – 21st, 2025, Erice, Sicily
- "Nuclear Photonics 2025" - 5th International Conference on Nuclear Photonics, Organizers: N. Pietralla, V. Bagnoud, October 06th – 10th, 2025, Darmstadt, Germany
- "HFHF Evaluation 2025", Organizers: F. Nerling, T. Aumann, C. Fischer, and the GSI representatives of the HFHF Academic Council Y. Leifels and T. Stöhlker, October 13th – 14th, 2025, Darmstadt, Germany

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[3] Varga, L.; Glorius, J.; Aliotta, M.; et al, "Nuclear Astrophysics in the Storage Ring: Background Suppressed Simultaneous Measurement of (p, γ) and (p, n) Reactions", Physical review letters 134(8), 082701 (2025), doi: 10.1103/PhysRevLett.134.082701

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[6] Schippers, S.; Brandau, C.; Fuchs, S.; et al, „Testing Strong-Field QED to Second Order in the Highly Correlated Atomic System Berylliumlike Pb78+ by Electron-Ion Collision Spectroscopy", Physical review letters 135(11), 113001 (2025), doi: 10.1103/6j3v-lwxj

[7] Mollaebrahimi, A.; Walls, C.; Dickel, T.; et al, "Precision Mass Measurements Reveal Low Neutron Pairing in Tin beyond N = 82 and Its Impact on Stellar Nucleosynthesis", Physical review letters 134(23), 232701 (2025), doi: 10.1103/ctyj-ls15

[8] Lykiardopoulou, E. M.; Walls, C.; Bergmann, J.; et al, "Refined Topology of the N = 20 Island of Inversion with High Precision Mass Measurements of 31−33Na and 31−35Mg", Physical review letters 134(5), 052503 (2025), doi: 10.1103/PhysRevLett.134.052503

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8.2 Activities and offers of the Helmholtz Graduate School for Hadron and Ion Research

Head: Prof. Dr. Henner Büsching (Goethe University Frankfurt)

Authors: Henner Büsching (Goethe University Frankfurt), Gerhard Burau (GSI)

Introduction

GSI and FAIR offer an outstanding setting for doctoral research and structural doctoral training. In strong cooperation with the partner universities of GSI and HGS-HIRE, young researchers are prepared for future careers inside and outside of academia and science. A key building block in this environment is the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe) at GSI-FAIR.

HGS-HIRe conducts structured doctoral training in all research fields of GSI and FAIR since October 2008. In addition to a variety of doctoral training measures, the Graduate School provides individual support as primary contact and care centre for doctoral researchers in its structured program. At the end of 2025, more than 350 doctoral students, conducting their research on GSI-FAIR related topics, were enrolled as participants in the HGS-HIRe program. 50 of them have been newly accepted for participation in the program of HGS-HIRe during 2025, 57 doctoral researchers affiliated with HGS-HIRe successfully completed their doctoral projects by defending their doctoral theses in 2025. The governance structure of the Graduate School, including the HGS-HIRe Management Board and the HGS-HIRe Administrative Office as well as the HGS-HIRe Application Review Committee, has continued to prove highly efficient in the daily work of the Graduate School.

Highlights in 2025

In line with the developments in the previous year, the expansion of the Graduate School's program activities continued in 2025 after the challenging impact of the pandemic years. Compared to 2024, this led to further increase in the demand for individual travel support of the HGS-HIRe participants to participate in conferences, workshops, and the HGS-HIRe Abroad Program. Furthermore, the residential face-to-face program has been strengthened again. This is seconded by HGS-HIRe online events as established in previous years. The following scientific training events, organised or offered by HGS-HIRe – partially in cooperation within the HGS-HIRe network – as residential face-to-face events in 2025, are particularly worth mentioning:

- Joint CRC 1245 & HGS-HIRe Lecture Week on Nuclear Ground-state Properties in Darmstadt, May 13-15, 2025 (organised by the Doctoral Students Representatives of the CRC 1245 and jointly offered within HGS-HIRe)
- International Summer Student Program at GSI-FAIR, July 21 - September 11, 2025 (training event for graduated students from GSI-FAIR partner countries; planned, organised and conducted in cooperation with a local team at GSI-FAIR)
- Joint CRC 1245 & HGS-HIRe Lecture Week on Effective Theory on Nuclear Interactions in Darmstadt, August 18-20, 2025 (organised by the Doctoral Students Representatives of the CRC 1245 and jointly offered within HGS-HIRe)
- Joint CRC-TR 211 & HGS-HIRe Power Week on Clean Software Development in Laubach, October 6-10, 2025 (method training workshop with introductory lectures, use cases and a strong focus on hands-on sessions)
- HGS-HIRe Participants Education Project (PEP) on Introduction to Tracking in Frankfurt am Main, November 17-19, 2025 (workshop, organised by HGS-HIRe participants, combining introductory lectures with extensive hands-on exercises)

In its well-established transferable skills training program, HGS-HIRe was able to keep the high number of supportive training events in 2025 basically on the same level as in the previous year. Altogether, in 2025 eight interactive transferable skills courses as part of an integrated series of courses, covering beginner's and advanced courses, with a total of 145 participants have been organised and conducted by HGS-HIRe together with the long-term, experienced trainer team from Great Britain. The courses were mainly organised and offered as residential face-to-face courses and supplemented by two online courses. As in previous years, it was possible to attract doctoral researchers from other Helmholtz Graduate and Research Schools to attend these courses, leading to a more interdisciplinary learning environment and group structure in the courses and, moreover, an ongoing Helmholtz-wide networking.

The HGS-HIRe information and supervision concepts including individual thesis advisory committees and online formats developed by HGS-HIRe to enable various contact and care offers have successfully been continued, too. In particular, the following supporting information and training events complemented the program offers in 2025:

- Quarterly HGS-HIRe Information & Contact Sessions for participants (online)
- Get-together for Doctoral Researchers at GSI-FAIR in cooperation with the HGS-HIRe Participants Representatives, the Human Resources Department of GSI and the Welcome Office at GSI-FAIR (face-to-face on the GSI-FAIR Campus)
- HEPTrepreneurs episodes by HEPTech in collaboration with the Technology Transfer (TT) Divisions at GSI-FAIR and CERN (hybrid)
- Helmholtz Career Day for Data Science 2025 (online conference to kick-start the career of young scientists in Data Science and IT at Helmholtz) and various training and information events offered by the Helmholtz Open Science Office (online and face-to-face)

In the HGS-HIRe Self-Service Centre – the internal service platform for HGS-HIRe participants – information on additional advisory offers and services at GSI-FAIR, the partner universities and internal and external training events and course offers within the Helmholtz community are provided. Among these, external residential and online 'power weeks', i.e. training events on specialised scientific and technical aspects and methods, as the 10th Data Science Symposium 2025 – organised by Hereon and the Helmholtz Coastal Data Centre (HCDC), and a wide range of training courses and online lectures on computer and data science related topics offered by the Helmholtz Information & Data Science Academy (HIDA), Helmholtz Federated IT Services (HIFIS), and the Centre for Information Services and High Performance Computing (ZIH), respectively, supplemented the scientific training program of HGS-HIRe in 2025.

A new element within the HGS-HIRe program of 2025 was dedicated to the topic of "Mental Health Support". The ability to cope with difficult events and situations and the question how one can recover got more widespread attention in recent time. In cooperation with the HGS-HIRe Doctoral Representatives, HGS-HIRe started a new format to address these and other related topics: A practical online training course on so called "Mindfulness-based Mental Resilience" that started with an orientation session followed by a kick-off workshop and 16 sprint workshop sessions. This online training addressed the foundations of resilience and delivered useful tools doctoral researchers can start using immediately in their daily work. The training was offered to all doctoral researchers interested in this topic and was very well received by the participants.

Outlook 2026

In summary, HGS-HIRe has continued its efforts to strengthen its structured program offers, including an increased number of residential face-to-face training events seconded by online courses and supportive information events, and to develop it further in 2025. For 2026, it is planned to continue to offer a correspondingly broad and attractive program for doctoral researchers in the GSI-FAIR research and training environment.

8.3 ExtreMe Matter Institute EMMI

Head: Prof. Dr. Peter Braun-Munzinger (University Heidelberg & GSI)

Author: Carlo Ewerz (GSI & University Heidelberg)

Introduction

The ExtreMe Matter Institute EMMI at the GSI Helmholtzzentrum für Schwerionenforschung is dedicated to fostering experimental and theoretical research on matter under extreme conditions of temperature and density. The forms of matter investigated by EMMI include the hottest, coldest and densest forms of matter in the Universe.

EMMI was founded in the framework of the Helmholtz Alliance "Cosmic Matter in the Laboratory" (2008-2015). The Alliance connected more than 400 scientists at the 13 partner institutions of EMMI in their study of various forms of strongly coupled matter. EMMI is now a permanent part of the GSI/FAIR research division and continues the collaborations that have been established within the framework of the Alliance. The research areas of EMMI range from the quark-gluon plasma as it existed shortly after the Big Bang, to hadron physics, to hot and highly compressed electromagnetic plasmas, to atomic physics in extreme fields, to the dense medium of neutrons that governs supernovae and neutron stars, and to ultra-cold quantum gases. Despite sometimes dramatic differences in density, temperature, field strength etc. (sometimes the differences are more than 20 orders of magnitude) such systems exhibit remarkable similarities, for example in the emergence of characteristic collective behaviour of many particles. The key idea of EMMI is to conduct research in an interdisciplinary framework, based upon the common underlying concepts for the theoretical and phenomenological understanding of the phenomena that occur in different forms of strongly coupled matter.

Among its activities, EMMI organizes topical and interdisciplinary workshops and research programs. As a new, additional workshop format EMMI introduced Rapid Reaction Task Force meetings which bring together a group of about 15 to 25 world-leading experts in order to address a focused scientific problem in intense discussions. Usually, the results of these meetings are summarised in a publication. As a further element for strengthening the international networking, EMMI runs a very active visitor program, in particular with the EMMI Visiting Professorships.

EMMI is dedicated to scientific excellence, equal opportunity and diversity, and the promotion of early-career scientists. It is the explicit strategy of EMMI that its scientific meetings should be geared towards these objectives. EMMI encourages in particular the active participation of early-career scientist in all EMMI scientific meetings.

EMMI Partner Institutions: GSI Helmholtzzentrum für Schwerionenforschung, Forschungszentrum Jülich, TU Darmstadt, U Frankfurt, U Heidelberg, U Münster, FIAS Frankfurt, MPI für Kernphysik Heidelberg, Sorbonne Université Paris (France), U Tokyo (Japan), Joint Institute for Nuclear Astrophysics JINA (USA), Lawrence Berkeley National Laboratory LBNL (USA), RIKEN (Japan)

Activities in 2025: EMMI events

- EMMI Workshop "Nucleosynthesis of heavy elements: r-process", Organizers: A. Flörs, M. Molero, A. Arcones, A. Bauswein, C. J. Hansen, G. Martínez-Pinedo, January 20-25, 2025, Hirschegg, Austria
- EMMI RRTF "Next generation facility of forward physics at the LHC", Organizers: R. Schicker, A. Szczurek, February 17-21, 2025, Heidelberg, Germany
- EMMI Workshop "54. Arbeitstreffen Kernphysik (54. Workshop on subatomic physics)", Organizers: F. Maas, S. Bacca, P. Braun-Munzinger, E. Epelbaum, S. Masciocchi, S. Paul, J. Wambach, February 20-27, 2025, Schleching, Germany
- ECT*-EMMI/GSI Workshop "Non-equilibrium phenomena in superfluid systems: atomic nuclei, liquid helium, ultracold gases, and neutron stars", Organizers: B. Haskell, P. Magierski, G. Roati, G. Wlazłowski, May 12-16, 2025, Trento, Italy
- EMMI Workshop "Soft photons - the higher orders", Organizer: K. Schweda, May 26, 2025, Heidelberg, Germany
- EMMI Collaboration Meeting, "QCD at FAIR – A cross-community driven hadron physics program at GSI/FAIR", Organizers: F. Nerling, J. Messchendorp, A. Pilloni, I. Vidana, June 22-27, 2025, Sicily, Italy
- ECT*-EMMI/GSI Workshop "Penetrating probes of hot high-μ_B matter: theory meets experiment", Organizers: T. Galatyuk, M.P. Lombardo, R. Rapp, E. Scomparin, G. Usai, July 21-25, 2025, Trento, Italy
- EMMI Workshop "He burning and perspectives for underground labs - HELIUM 25", Organizers: E. Masha, J. Skowronski, L. Barbieri, A. Boeltzig, F. Cavanna, D. Piatti, M. Pichotta, S. Turkat, B. Wehmeyer, A. Yadav, July 21-25, 2025, Dresden, Germany
- EMMI Physics Day, Organizers: K. Blaum, P. Braun-Munzinger, C. Ewerz, July 22, 2025, Darmstadt, Germany
- EMMI Workshop "Nuclear masses in astrophysics for the next 25 years", Organizers: K. Blaum, A. Estrade, A. Kankainen, Y. Litvinov, Z. Meisel, S. Porter, August 18-22, 2025, Darmstadt, Germany
- EMMI Workshop "Synthetic topological matter (SYNTOM)", Organizers: T. Grass, S. Jochim, B. Juliá-Díaz, L. Tarruell, C. Weitenberg, August 31 - September 6, 2025, Benasque, Spain
- EMMI Workshop "Collective phenomena and the equation-of-state of dense baryonic matter", Organizer: B. Kardan, J. Noronha-Hostler, T. Reichert, November 10-13, 2025, Darmstadt, Germany
- EMMI Workshop "5th Workshop on Anti-matter, hyper-matter and exotica production at the LHC", Organizers: S. Bufalino, A. Calivà, B. Dönigus, J. Schaffner-Bielich, November 10-14, 2025, Salerno, Italy

9. Accelerators, Detectors, Electronics and IT

9.1 Activities of the Department Experiment Electronics

Head: Dr. Thomas Bretz (GSI)

Authors: J. Adamczewski-Musch, H. Brand, H. Flemming, K. Koch, N. Kurz, M. Traxler

Introduction

Experiment Electronics (EEL) provides data acquisition support for the FAIR Phase-0 experiments. This includes the design and fabrication of various new hardware and hardware components, including the necessary control and analysis software. The department assists with installation and provides support for installed systems. Experiment Electronics develops application-specific integrated circuits (ASIC), analog and digital electronics, and the necessary printed circuit boards (PCB). The department's own production enables short development cycles for prototyping, but also for the production of larger quantities. With the Multi Branch System (MBS) and the Data Acquisition Backbone Core (DABC) two data acquisition solutions are actively developed and supported, which complement the offered data acquisition hardware. For data analysis, the Go4 system meets the needs of the ever-increasing requirements for experimental setups towards FAIR. An essential backbone for the success of any experiment is a robust and reliable control system. Support for various such control systems, mostly based on LabVIEW, EPICS, C++ and Python, is offered. In addition to common large-scale systems, Experiment Electronics provides support and solutions for everyday challenges in facilities and laboratory setups.

Highlights in 2025

Control Systems

Control Systems at GSI widely utilize National Instrument's (NI) LabVIEW. For cost reasons, the NI Enterprise Agreement has been terminated by the end of 2025. Inventory perpetual licenses have been reactivated, a few additional licenses, mostly deployment licenses have been purchased, causing one-time cost only. Projects still using LabVIEW froze the LabVIEW version. The control systems group is continuously working on the migration of LabVIEW projects by consulting and active support.

The migration of the target scanner project serves as example. It utilizes an asyncio approach based on Python/PyAcdaq (https://git.gsi.de/EKS/Python/ACDAQ/PyAcdaq, https://git.gsi.de/EKS/Python/ACDAQ/TargetScanner) implemented on a Raspberry Pi with a tkinter based graphical user interface and MQTT as message protocol. SHIPTRAP's control system has been migrated to EPICS utilizing the MUPPET module as replacement for NI-RIO (FPGA) with improved resolution and accuracy (https://git.gsi.de/EKS/Python/MUPPET). The Windows based *Mass Measure* GUI (MM6) has been migrated to Linux (https://gitlab.msu.edu/lebit-controls-and-analysis/mm8).

EPICS consulting in support of HADES, CBM, NUSTAR and PANDA continues, either in the form of initial kick-off meetings or continuous project support (for HADES and CBM). The new HADES magnet control system MCS was successfully used in the recent productive spring beamtime. After consolidation, this project is on track to serve. The project coordination of CBM's Detector Control System (DCS) Project got leveraged by a new cooperation with the Chinese Institute of Modern Physics (IMP) accompanied by a successful DCS workshop in April 2025 (https://indico.gsi.de/event/21972) and by this CBM reassessed the DCS project importance, leading to ongoing shared leadership of the DCS project by Min Li (IMP) and Peter Zumbruch (GSI) since October 2025.

Manufacturing

One of the highlights of the electronics department at GSI is our own assembly facility for printed circuit boards (PCB). Electronics circuits, developed for cutting edge experiments, have to be disentangled, and printed circuit boards designed before production. After the printed circuit boards are manufactured by external companies, our production chain is used to mass-produce the end product. The assembly of these high-end PCBs with state-of-the-art components (as small as 400µm times 200µm) in house gives us the major advantage of a short feedback loop between the assembly group, the layout group and the developer which results in a much faster optimization process for the electronics production. This allows the delivery of reliable electronics modules (high quality production) in the required time frame.

During 2025, 77 different printed circuit boards, which totalled to 4958 PCBs, were assembled in our facilities. A larger fraction was for the Accelerator Controls - ACO department (FG900.251, FG900114_SCU4-1) and the Detector Laboratory (FEB8-2_Av4 and FEB8-5_Av3).

Analog Design

In the year 2025, an analogue multiplicity trigger module was designed, developed, and implemented as a fully operational hardware system (see Figure 65). The circuit was specifically tailored to meet the requirements of the BPLAST detector within the DESPEC experiment. At the same time, particular emphasis was placed on a generic design in order to facilitate straightforward adaptation and deployment in other particle detector setups.

The module provides fast and direct signal processing based entirely on analogue techniques. Incoming detector signals are combined through an analogue voltage summation, enabling very low processing latency. The device offers 16 individual NIM logic input channels.

For further processing of the summed signals, two independent NIM logic output channels are available. Each output features a dedicated adjustable comparator. The selected comparator threshold directly defines the desired trigger multiplicity.

The device has already been successfully deployed at GSI during the G302 and S115 experiment runs at the BPLAST detector, where it was used to suppress large amounts of uncorrelated background and noise signals and to trigger on time-correlated hit signatures relevant to the experiment.

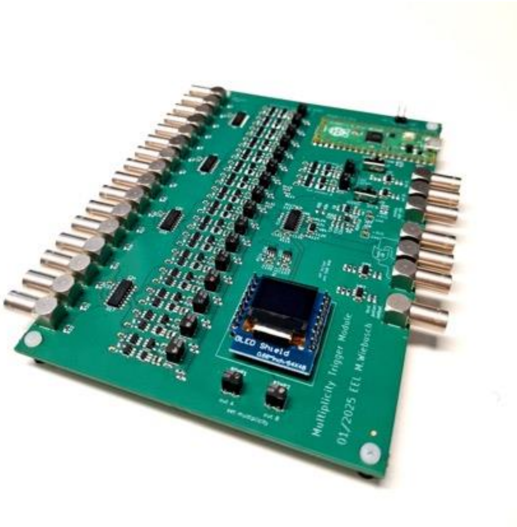

Figure 65: Picture of the multiplicity trigger module board.

Digital Electronics

We have developed a new high-throughput framework for TDC readout on FPGAs which is easily portable to many architectures, as it is VHDL-code without utilizing architecture specific features (implemented already on Lattice ECP5 and CertusPro-NX); see Figure 66. The key advantages are compression, which makes the data more than 25% smaller (compared to the data format which is used in the readout of the currently used generation of FPGA-TDC-based systems), enabling higher effective data throughput, and a unified architecture, which allows different types of TDCs to be easily integrated. The TDC we ship with this framework has a precision of approximately 15 ps RMS. This readout framework is meant to be used on our new TDC board, which supports 10 Gb Ethernet for data transfer, further increasing the overall throughput of our system by an order of magnitude.

During 2025, a compact front-end electronics system specifically tailored to the technical requirements of the Super-FRS tracking detectors was developed for the SCIFI (SCIntillating FIber) tracking detectors at the Super Fragment Separator (Super-FRS), and an initial FOS series was produced (see Figure 67). The SCIFI_652 front-end electronics is a modular, stacked system consisting of a SiPM sensor module, an amplifier module, and an FPGA-based TDC module, each designed for 128 channels. The system is completed by an interface module equipped with two optical transceivers for serial clock/trigger and data links. In addition, the interface module hosts the voltage regulators to power all components of the electronics from a single external bus voltage. In December, the first FOS Super-FRS SCIFI tracking detector equipped with the new SCIFI_652 front-end electronics was assembled and commissioned, and has already successfully completed an initial test beam campaign at the Heidelberg Ion Beam Therapy Centre (HIT). The first results show that the main functionality is given. A detailed analysis of the data will follow.

For the STAR experiment in Brookhaven an opportunity arose for obtaining another beam time, a fixed target run ("FTX"), where the eTOF is needed for increasing the acceptance (see Figure 68). For that we replaced all pre-amplifier PCBs, in total 216 circuit boards. They were damaged in the last run due to so called "beam loss events", which induced unexpected high voltage spikes at the input of the pre-amplifiers. The new electronics was improved with ESD protection which solved this problem. To exchange the electronics, the detector had to be completely disassembled, the modules opened, and then reassembled. Thanks to this successful measure, STAR management was able to apply for additional beam time at the DOE for the FTX program. We hope for successful beam time at the end of January.

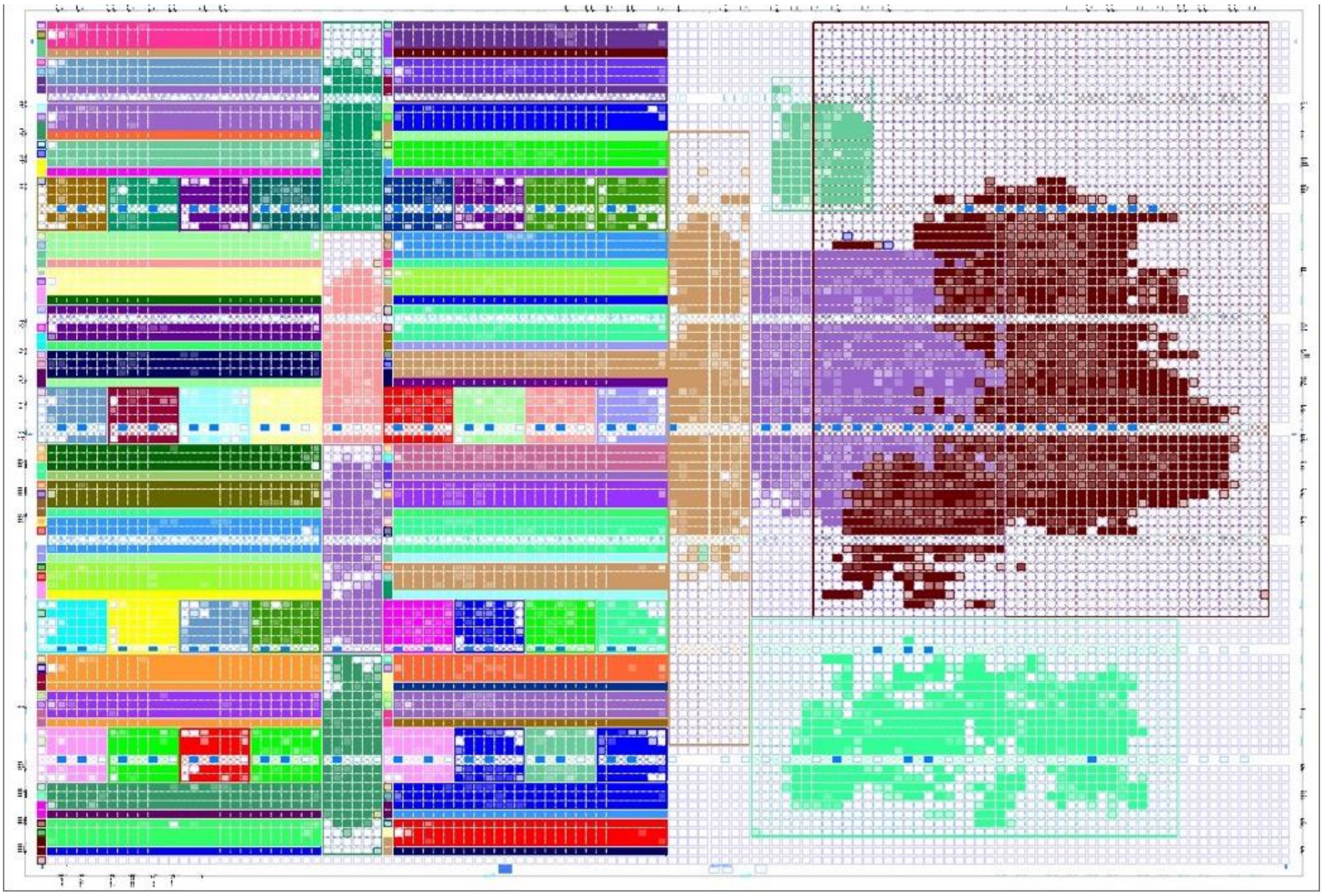

Figure 66: “Floorplan” of the FPGA of the newly developed readout and TDC. The fact that all logic for the 32 channels is located on one side of the FPGA allows that place & route for the readout and TDC to always succeed.

Figure 67: 6 SCIFI modules are chained for one SCIFI-detector.

Figure 68: eTOF modules of STAR. Our electronics is located in the middle.

Data Acquisition and Analysis

The data processing team of EEL department takes care of data acquisition (DAQ) and monitoring systems of *GSI* and *FAIR* experiments. This consists in developments of specific detector readout hardware, corresponding FPGA firmware, and software frameworks for data collection and quality monitoring on DAQ computer clusters.

New DAQ hardware systems for upcoming FAIR experiments are currently under construction. The 16-channel ADC transient recorder ASIC CTR16 (see below) is intended for operation at the Super-FRS. Such chip would be read out by the common MBS DAQ system with KINPEX (PCI express) data receiver boards via our proprietary GOSIP fibre link protocol. This setup requires new adapter boards for power distribution, control, and data transfer between the CTR16 ASICs and the KILOM2 front-end card (FPGA-based TDC), supporting long-distance LVDS links and extended power distribution. The corresponding firmware has been updated to support up to 32 CTR16 chips per KILOM2 card, with prototype production and testing scheduled for 2026. In addition, the Super-FRS experiment will deploy scintillating fibre detectors (SciFi) at the first beam. During the mentioned test beams at the HIT facility in Heidelberg, not only the hardware of the SCIFI_652 front-end cards were tested but also the developed firmware and operated successfully with the MBS DAQ.

Further improvements have been implemented for existing front-end electronics. The FEBEX sampling ADC system, as established for the super-heavy elements research (TASCA) and other GSI experiments, has been equipped with a new crate interface card. This enables transmission and reception of trigger and clock signals via fibre-optic links. The standard FEBEX4 firmware with a fast trapezoidal filter has been upgraded to support 5 Gb/s GOSIP data transfer. With regard to FAIR beam diagnostics application, FEBEX4 firmware for control and readout of the AWAGS ASIC was enhanced to enable recording of the beam spill structure. This feature has been successfully demonstrated during beam tests at GSI in 2025.

The Linux device driver libraries for the KINPEX (PCIe optical data receiver) board have been reviewed concerning the most recent developments of variable GOSIP link speed, and the improved DMA engine. This covers alternative implementations for different readout systems: MBS, DABC (or FESA), and a network device to receive GOSIP data via plain UDP socket.

The example user readout software for the MBS system has been reorganised. This features a well-arranged user software framework with implementations for commonly used readout systems. By means of the built-in MBS parser, the complete read-out may be configured from a text file which is engaged at acquisition start-up time. Still full user control of the source definitions at compile time is preserved. The new readout software is available as framework MURX (“Mbs User Readout for pci-eXpress”) for the PC based GOSIP link systems. The counterpart SMURV (“Standard Mbs User Readout for Vmebus”) is dedicated to all GSI supported VMEbus processors.

The ELDER analysis framework has been further consolidated at real experiments’ set-ups. ELDER offers configuration of data decoding and histogram displays for standard data acquisition front-end modules from a text file. Event stitching of time-sorted data streams and simple analysis algorithms may also be defined here. In the scope of the ROOT-based Go4 analysis environment, it is now possible to specify in the ELDER setup a custom output event data structure without recompiling the libraries.

Software for readout and monitoring of the new DAQ system DOGMA have been improved in the DABC data acquisition framework, and in the stream analysis plug-in for Go4. This includes performance optimizations by more efficient data formats of the DOGMA front-ends. Furthermore, DABC applications for event building and quality monitoring have been consolidated during the HADES production beam in April 2025. Last but not least, contributions to the JsROOT GUI of the ROOT analysis framework at CERN have been continuously provided, with impact on web-based analysis displays of numerous experiments.

Application Specific Integrated Circuits (ASIC)

Extensive measurements were done to characterize the second iteration of the CTR16 ASIC. Although originally designed for the read out of the Super-FRS GEM-TPC, it has the potential to become a general readout architecture for a wide spectrum of detector systems. One of the main components of the CTR16, the 12-bit pipeline ADC, was characterised on a separate test chip in collaboration with colleagues from the Helmholtz-Institute Mainz. These measurements have shown that the design has still some minor issues which have to be corrected in the next iteration. Generally, the ASIC shows an excellent performance.

In parallel, the ASIC design group participated in beam tests, e.g., of high dynamic range charge sensitive amplifier ASICs, which will be used in the beam diagnostics of FAIR and GSI accelerators and Super-FRS. We also supported the beam time of FRS with our expertise.

Beside the concrete design work intensive discussions concerning future development of ASIC design at GSI took place. The evaluation report of the Helmholtz society for the matter and technology program recommends to strengthen the ASIC design at GSI. In experiment groups there is the wish to establish pixel sensor design at GSI which is strongly connected to ASIC design. So, there are discussions ongoing and will be continued in 2026 how this could be realised and how the current ASIC design group could play a part in this development without harming the very successful current work.

9.2 Activities at the Department Detector Laboratory

Head: Dr. Christian J. Schmidt (GSI)

Author: Christian J. Schmidt

Introduction

As the host laboratory for the GSI and FAIR accelerator facilities, GSI and with it the department Detector Laboratory DTL is committed to supporting its user community by providing advanced instrumental technologies to its research collaborations. With ever growing intensities and interaction rates but also with the enormous dynamic range of signals which detectors are confronted with at these heavy ion accelerator facilities the technological focus lies primarily on particle tracking detectors, their readout and system operation. This group of detector applications imposes the predominant technological challenge for the science case as it is projected at GSI and FAIR, but also other detector applications are addressed at DTL. In alignment with the ECFA detector roadmap, DTL seeks international collaborations to enhance its technological capabilities in gaseous detectors (DRD-1) while building increasing competence in state-of-the-art silicon tracking detectors (DRD-3).

Highlights in 2025

TPC detectors

Within this mission, DTL performs fundamental research on TPC detectors, which remain the tool of choice for applications demanding to combine precise low momentum tracking and lowest material budget with advanced spatial resolution and dE/dx particle identification capability. In the prospective of future FAIR upgrades, particular challenges consist in adapting this detector concept to higher rates. Novel MPGD structures and hybrid stacks integrating micro-RWELL structures, Gas Electron Multiplier foils (GEM) with novel coating materials and resistive electrodes are being studied aiming to obtain this goal and simultaneously to improve the gain, energy resolution and the ion-backflow ratio of the detectors. These activities are currently being embedded in the ECFA-DRD1 collaboration, where the work with heavy ions implies a special trait and ingredient.

The need to make TPCs robust to the high energy deposition (dE/dx) motivated the development of Multi Sampling Ionizing Chamber (MUSIC), which provide simultaneously precision tracking and identification of relativistic heavy ions and their fragments in magnetic separators e.g., at the FRS at GSI and the Super-FRS under construction at FAIR. Primary R&D goals for next generation MUSIC detectors consist further improving their outstanding robustness to the impinging, highly ionizing heavy ions, their capability of identifying particles by means of dE/dx over a wide charge range (the additional degree of freedom in the work with heavy ions), and to improve their tracking precision toward ~100 µm at highest rates.

This led to the construction of several advanced detectors like the TPC projected by the HYDRA (HYpernuclei Decay at the R3B Apparatus) physics program of the R3B collaboration. HYDRA aims to perform decay spectroscopy of hypernuclei produced in heavy ion collisions at GSI/FAIR. Being located inside the 5 Tm GLAD magnet of R3B, this TPC is to measure with high resolution the in-flight pionic decay of light and medium mass hypernuclei. Being designed at TU Darmstadt, HYDRA employs an innovative hybrid amplification stage of a GEM stacked with a Micromega (MMG).

MUSIC detectors are operated in a pocket in vacuum, which creates multiple integration challenges and imposes the need for relatively heavy vacuum windows within the spectrometer, which compromise the measurement precision. Future research aims to develop a MUSIC operating at a reduced gas pressure of 20-100 mbar to minimize decisively the material budget of those vacuum windows. Realizing this approach was identified as key strategic development target for future gaseous detector developments in FAIR.

The TPC developments are complemented by the "Active Target for FAIR" (ACTAF) TPC. Operated with H_2 or He gas at high over-pressures up to 20 bar, the 1.5-meter-long and 1-meter-diameter detector serves as both, target, and detector for precision measurements, such as elastic proton scattering at intermediate energies. It provides access to the full reaction kinematics, including those of recoil particles. This capability offers experimental insight into nuclear matter radii and the radial distribution of nuclear matter, which are not accessible otherwise. Precision measurements of these parameters are considered critical missing components of nuclear structure theories and astrophysics.

Scintillating fibre trackers

Particle tracking at rates way above the one of TPCs can be carried out by scintillating fibre trackers (SciFi Tracker). Such technology that also provides extremely large dynamic range for dE/dx measurements was developed at DTL. A production process for single layer fibre ribbons could be established. Scintillating fibres with square cross section were used to build up detection planes of highest homogeneity in material budget. The fibre ribbon comprising one or even three layers of fibres is read out by a one-dimensional array of Silicon Photomultipliers (SiPM) coupled to custom developed readout electronics (see Figure 69). The detector concept of scintillating fibre tracking planes is so promising that it was chosen as the preferred technology for three experiments in the Early Science Program at FAIR. These include the Super-FRS and R3B heavy ion tracking detectors, as well as the R3B Proton Arm Spectrometer (PAS), where 3-layer ribbons are utilised.

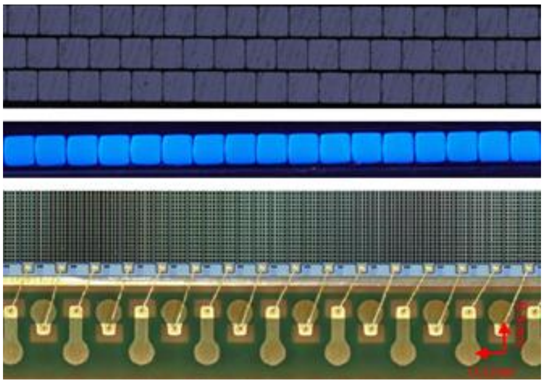

Figure 69: Cross-sectional view on a three-layer fibre ribbon (top), a one-layer fibre ribbon (middle) and the wire bonded SiPM array for readout.

Silicon tracking detectors

An even higher rate capability, being combined with way superior spatial resolution, is provided by silicon tracking detectors. Given the increasing demands of present and future FAIR experiments, GSI and with it DTL is expanding its expertise in this area and joins research collaborations providing access to cutting edge technologies in the field among others within the ECFA Program DRD3.

The ongoing activity in this direction is the realization of the Silicon Tracking Detector STS for CBM (see Figure 70), which forms a major contribution to FAIR. The detector integrates double sided silicon micro strip sensors into an extremely light and air-cooled high-rate tracking detector. While past work focused on the R&D of the sensors by themselves and their related DAQ system, the research focus of GSI and its numerous partners throughout the duration of this report shifted toward solving the numerous non-trivial questions of mechanical and electronic system integration and the cooling of the detectors. Additionally, multiple procedures and technical solutions on quality assurance for serial production had to be established [1][2][3][4][5]. Milestones of the activity include the completion of sensor production by Hamamatsu Photonics (2021), the finalization of the STS-XYTER readout ASIC (2022), the completion of the design of the front-end boards (2023) and the successful micro-cable production with the industrial partner LTU in Kharkiv, Ukraine (2024). The project also included regular system tests of prototypes within the FAIR phase-0 mCBM project and the test of pre-series modules in the partner project E16 at KEK/J-PARC, Japan.

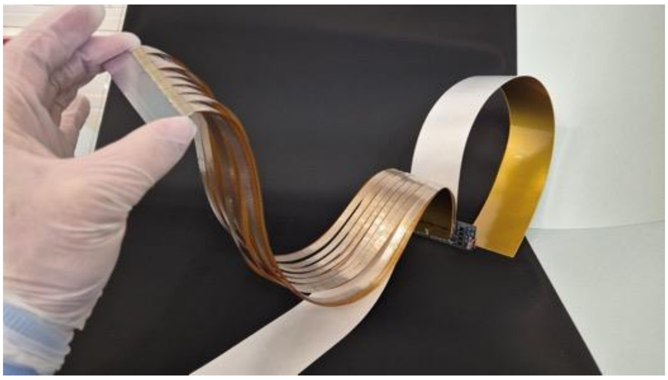

Figure 70: Example of a CBM-STS detector module where the small sensor will be allocated in the area of highest irradiation and the extremely long micro cables connect 2048 detector channels to the corresponding readout pre-amplifier chips outside the acceptance.

CMOS Monolithic Active Pixel Sensors (MAPS)

A spatial resolution and light material budget beyond the reach of silicon strip sensors is provided by CMOS Monolithic Active Pixel Sensors (MAPS). Research on the typically 50µm thin and flexible sensor was carried out with the perspective on the CBM Micro Vertex Detector (CBM-MVD) and a future CBM-STS upgrade. In collaboration with IPHC Strasbourg and Goethe University Frankfurt, the 60 µm thin MIMOSIS-1 MAPS prototype was developed, realised in TJ 180 nm technology, and integrated into an air-cooled six planes telescope assembly. Spatial resolution of ~5 µm (s), time binning of 5 µs and radiation tolerance to 50 kGy and 1×10^{14} n_{eq}/cm^2 was demonstrated in line with the CBM requirements [6]. Further, within the Helmholtz Innovation Pool project SOPHIE the feasibility of direct optical readout from the sensor is being elaborated.

Low Gain Avalanche Diode (LGAD) technology

While excelling in terms of best spatial resolution, light material and small power, the time stamping capability of MAPS leaves room for improvement. The complementary, ultra-fast Low Gain Avalanche Diode (LGAD) technology is being introduced at GSI in order to fill this gap. Their novel detector concept allows for simultaneously measuring the particle position with tens of µm spatial resolution and the time with ps precision, so-called 4D-tracking [7]. The excellent 4D-tracking properties are vital to cope with the increasing particle rates and are very essential for particle identification through time-of-flight (TOF) in modern nuclear and heavy ion physics experiments. The sensor technology was developed and promoted in cooperation with Fondacione Bruno Kessler (FBK) [8].

CVD diamond detectors

While usage of diamond detectors in large size tracking detectors is no further considered due to the difficult access to this material, detectors relying on CVD diamond material remain the best choice in some special cases. This holds in particular for small applications where the additional material costs with respect to silicon are acceptable given the substantial advantages of diamond material in terms of radiation tolerance and thermal stability. The GSI Detector Laboratory provides CVD diamond detectors for various applications which can mostly be classified as direct in-beam detection. Detectors are constructed from commercially available CVD diamond material of highest purity, which can be single-crystal (SC) or polycrystalline (PC). While the latter are used in timing applications as well as for current measurements, SC detectors also provide very good energy resolution. Following the research profile of GSI and FAIR, those detectors are optimised for direct detection of various ions in different energy regimes. Here it is worth to highlight the LISA experiment at HISPEC/NUSTAR where a stack of SC diamond detectors is used as a solid-state active target. Due to the limited size of individual crystals, detection planes are assembled as a mosaic and staggered along the beam axis (HISPEC/DESPEC). Other exceptional applications realised with diamond detectors at GSI are the operation in ultra-high vacuum (UHV) at CRYRING (2023), ultra-high speed through thin windows for Plasma Physics (2023), monitoring detectors for material sciences (2023), the multi-strip diamond TOF-start detector at mCBM (2024, 2025) and position sensitive detectors for Atomic Physics as well as continued R&D on several additional detector stations for SFRS.

Activities in 2025

In 2025, DTL was almost entirely engaged in the serial production of detector systems for the FAIR phases ES, FS and FS+. All these engagements are long standing activities that have now gone into production phase.

The Silicon Tracking System (STS) is the central, highly granular detector of the CBM experiment. It tracks charged particles created when nuclear beams from the SIS100 accelerator hit a target.

Positioned inside CBM's superconducting magnet, the STS is the only detector in the setup that can measure particle momentum. The CBM STS is GSI's largest in-kind contribution to FAIR experiments. It is realised in a joint effort by the two departments CBM and the detector laboratory DTL.

Today and since 36 months, the STS is in full serial production at the clean rooms of the detector laboratory as well as in the partner laboratory at the Helmholtz Centre KIT. Out of 876 detector modules already 786 have been assembled (90%). Further, integration of modules onto a total of 106 detector "ladders" comprising about 8 to 10 modules in a linear assembly has successfully been realised for one quarter of the modules.

Now the team engages into final system assembly where all the ladders will be integrated into the final CBM-STS housing that will be allocated inside the CBM magnet. Final testing and module qualification takes place at GSI, with involvement of students and team members from Germany, Poland and Ukraine.

DTL provides instrumentation for high energy beamline diagnostics as GSI in-kind. Production of the full volume of 42 devices has been finalised in 2025. Out of these, 12 with an additional extra of 2 spare devices have been fully qualified and delivered to FAIR early science (ES).

For Super-FRS at FAIR, DTL provides two Multi Sampling Ionization Chambers (MUSIC) for each of the phases FAIR ES as well as FAIR FS. Here the first two devices for ES will be provided until early 2026, while prototyping and beam test in 2025 initiated final design modifications.

The GEM-TPC is a device to allow for particle tracking through the Super-FRS. Operation in phase FS will rely upon 14 of these detector systems which are a Finish in-kind. These detectors have been developed in a long-standing cooperation between HIP and GSI. For serial production, DTL will provide the field cages, a key essential subassembly of these instruments. The completion of the first two FoS units is in preparation for early 2026.

During ES, tracking through the Super-FRS will be realised by means of scintillating fibre trackers. Scintillating fibre-based trackers were successfully developed at DTL in 2025. A production process for single layer fibre ribbons was established. Scintillating fibres with square cross section are used to build ribbons of highest homogeneity. The fibre ribbon is read out by one dimensional SiPM arrays coupled to custom developed readout electronics. Though not as radiation tolerant on the long run, such fibres are considered the robust and reliable heavy ion tracking solution for day one of Super-FRS and R3B operation as well as for the R3B proton arm operation.

Two First of Series Detectors were built and were successfully tested in beam times at GSI. Now serial production for Super-FRS and PAS has started at the GSI lab in Q4 2025.

The detector laboratory also provides services related to the preparation and installation of diamond detectors in various setups in GSI and FAIR. For the Super-FRS target chamber two in-beam diamond detectors were constructed for the use in ES and prepared for installation into the chamber. The LISA experimental setup at NUSTAR, on the other hand, is based on an active target made out of more than 100 single crystal diamond sensors arranged in an overlapping mosaic multi-layer pattern. Each sensor was prepared, characterised, and mounted at DTL with active participation of LISA members and successfully commissioned in-beam at FRS.

Outlook 2026

The year 2026 will be a busy year dedicated to detector production and eventually detector commissioning, addressing the completion of the CBM STS assembly, the production of Super-FRS tracking detectors and in particular the fibre tracking devices thought as day one instrumentation of the Super-FRS in the ES phase in place of the GEM-TPC devices. On CBM-MVD integration, DTL will assist but the project drivers are here University Frankfurt, GSI DTL will provide assembly infrastructure.

Selected publications

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9.3 Research of the IT Department

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Introduction

Following the significant developments in scientific computing and data management detailed in previous reports, the IT department has continued to evolve and make substantial progress across multiple domains throughout 2025. This report illuminates key achievements and advancements made by different groups within the department. Central to realizing the GSI/FAIR mission, the IT Department remains dedicated to fostering unparalleled expertise in the technical analysis, design, implementation, operation, and support of vital computing infrastructure and services [1].

Highlights in 2025

Expanded Computational Capacity Meets Growing Scientific Demand

The generic GSI cluster has been successfully expanded by 30,000 CPUs, bringing the total capacity to 100,000 CPUs. This growth ensures our infrastructure can effectively support the GSI/FAIR experiment's computational workload, particularly as data volumes continue to increase with higher-intensity data acquisition periods [2].

Lustre Storage Infrastructure Modernization

The IT Department has implemented a diversified Lustre storage strategy through the deployment of a new high-performance filesystem (Idril), addressing growing data demands from FAIR experiments. This modernization features 5x faster disk failure recovery (9 hours versus 47 hours) through advanced ZFS capabilities, continuous filesystem monitoring via the Robinhood policy engine, and added 22 PB of capacity with 790 Gb/s of bandwidth from hardware renewal. The multi-system approach significantly enhances resilience by minimizing service disruptions while ensuring scalable, reliable storage for GSI/FAIR experiments.

Optimization of Tape-Based Archival Infrastructure for High-Throughput Data Management

The Storage/Data group has modernised its infrastructure through the development and deployment of purpose-built software tools, enhancing both automated tape archival workflows and data restoration efficiency. These tools streamline the migration of datasets from primary storage to tape media while significantly reducing restoration latency to target filesystems. To verify compliance with the throughput requirements of FAIR-based experiments (e.g., CBM), the infrastructure underwent 72-hour continuous stress testing during dedicated Data Challenges. The system sustained **≥2.0 GB/s** data transfer rates for both production ingest and archival operations, demonstrating readiness for large-scale experimental data preservation.

Evaluation of Enhanced Monitoring Architecture

To modernize our monitoring infrastructure, a comprehensive assessment was conducted for a new high-availability (HA) system capable of distinct long- and short-term data retention, prioritizing open-source solutions. The legacy stack (Prometheus with InfluxDB v1) required replacement due to limited HA capabilities and supply chain concerns regarding core components.

Several architectures were evaluated against criteria including HA robustness, open-source viability, scalability, and long-term support. Key alternatives assessed included VictoriaMetrics (dismissed due to sustainability concerns for the free tier), InfluxDB v3 (rejected for stability issues), and distributed Prometheus-based solutions (Thanos and Mimir). Thanos was selected as the preferred foundation, offering full open-source HA implementation with greater configuration transparency for our infrastructure scale.

For object storage, MinIO, Garage, and RustFS were reviewed. Garage was chosen for its stability, self-healing replication, and alignment with our local storage strategy, while MinIO's future open-source status and RustFS's immaturity were determining factors.

The final solution—**Prometheus + Thanos + Garage**—has been implemented via automated Ansible. The system is currently undergoing validation testing and is scheduled for production deployment in 2026, delivering a sustainable, HA-capable monitoring platform meeting all core requirements. Future evaluations of emerging tools (e.g., RustFS) will continue as maturity increases.

Direct Liquid Cooling Deployment Enables High-Density AI and HPC Infrastructure

In collaboration with Rittal, GSI-IT has successfully implemented a Direct Liquid Cooling (DLC) system featuring a Cooling Distribution Unit with over 1 MW of cooling capacity in a compact rack format. This solution addresses the critical thermal challenges posed by modern AI and High-Performance Computing workloads, which generate more than 150 kW of heat per rack—exceeding the physical limitations of traditional air-cooling systems. The implementation represents a pioneering effort in large-scale data centre liquid cooling, significantly enhancing energy efficiency. This initiative establishes a practical blueprint for future data centre infrastructure, demonstrating how direct chip cooling can support increasingly demanding computational workloads while maintaining sustainability goals and reducing the C02 footprint

LLMBot: Introduction of a Local Large Language Model Service at GSI

The IT Department introduced LLMBot, a locally hosted Large Language Model (LLM) service providing GSI/FAIR staff with access to state-of-the-art AI language models while keeping sensitive data within the institute's infrastructure. The service is built on the vLLM inference framework with OpenWebUI as the user-facing interface, deployed via Docker Compose on a dedicated server equipped with eight NVIDIA H200 GPUs. The production setup runs four concurrent model endpoints: a Qwen3-VL-235B-A22B-Thinking-FP8 multimodal reasoning model on four GPUs, a GPT-OSS 120B general-purpose thinking model on two GPUs, a Mistral Small 3.2 24B multimodal model on a single GPU, and a dedicated Qwen3-Embedding-8B model on the eighth GPU for Retrieval-Augmented Generation (RAG). The latter enables users to upload documents and query them semantically via a vector database. The model selection is configurable, making it straightforward to adopt improved models as they become available. Users can further define personal model configurations by combining any base model with a document collection and a custom system prompt, enabling domain-specific assistants. In addition to the web interface, the service exposes an OpenAI-compatible API, allowing programmatic access for integration into custom workflows. Access is managed through GSI's existing Weblogin (KeyCloak) OAuth infrastructure, and the service is exposed at https://llmbot.gsi.de for internal use. The deployment is designed to scale down to a single development machine, allowing the full stack to be tested and developed without production hardware. Following a development and testing phase, the service is currently available to CIT staff in a pilot phase.

JupyterHub Deployment for Secure Interactive access to the Virgo Cluster

A custom **JupyterHub** service has been developed to provide researchers with a secure, open-source platform for interactive Python-based data analysis and visualization [3]. Integrated with GSI's Virgo cluster via a purpose-built spawner, the solution enables seamless access to computational resources through a web interface without requiring privileged cluster access. User authentication leverages GSI's central Single Sign-on, with all cluster interactions secured via SSH.

This initiative enhances researcher productivity through real-time data exploration while optimizing cluster utilization. The service is currently in internal testing and will enter production in 2026.

RoCE and NVMe Storage System Validation

RoCE (RDMA over Converged Ethernet) enables high-performance, low-latency networking by allowing remote direct memory access over standard Ethernet, while NVMe (Non-Volatile Memory Express) is a high-performance storage interface designed specifically for modern solid-state drives. As part of a strategic evaluation of future network architectures, GSI-IT conducted with Huawei an initial Proof of Concept to assess whether to maintain our current InfiniBand infrastructure or transition to RoCE-based solutions. This foundational study validated NVMe-based storage operating on RDMA over Converged Ethernet, demonstrating high throughput performance while maintaining compatibility with GSI's existing infrastructure. The testing confirmed the technical feasibility of migrating from InfiniBand to RoCE with Lustre, though inter-leaf communication challenges required specific solutions. As this represents only the first phase of evaluation, additional testing, performance benchmarking, and cost-benefit analysis will be required before any final decision is made regarding whether to fully replace InfiniBand, maintain it alongside RoCE in a hybrid architecture, or adopt a phased migration approach.

DataHarbor: A Secure Web Portal for Large-Scale Data Access

DataHarbor is a modern, full-stack web application developed by the Software Development for Experiments (SDE) group in the GSI IT department to provide researchers with secure, intuitive access to large-scale data stored on GSI Lustre clusters through the XRootD protocol. Users access DataHarbor over HTTPS; the Vue.js frontend communicates only with the Go backend (BFF). The backend holds OAuth tokens server-side, validates them, and establishes authenticated, encrypted connections to XRootD storage, streaming file data through the backend to the user's browser using chunked transfer encoding with adaptive buffering. This eliminates intermediate storage while enabling efficient downloads of multi-gigabyte datasets over WAN connections. The architecture implements comprehensive security using the Backend-For-Frontend (BFF) pattern with OpenID Connect (OIDC) authentication via Keycloak. All OAuth tokens are stored exclusively server-side, and the frontend communicates only through HTTP-only, Secure, SameSite cookies over HTTPS, preventing XSS and CSRF attacks.

A key technical contribution of this work is the integration and extension of the native Go XRootD client from the go-hep.org/x/hep project to support Zero-Trust Networking (ZTN) protocol authentication combined with TLS encryption for native xrd:// connections. This enhancement enables secure, token-based authentication using OAuth tokens from Keycloak on native XRootD connections — a capability previously available only via HTTP-based access. The ZTN implementation validates tokens server-side through SciTokens, maps authenticated users to Unix credentials via the multiuser plugin, and ensures end-to-end encryption while preserving native protocol performance. DataHarbor reached version 1.0 in late 2025, featuring full Docker Compose deployment support, comprehensive CI/CD pipelines, and RPM packaging for production environments. The project is currently in the beta testing phase and is being deployed to the GSI production server.

Contributions to C++

In 2025, the features of the upcoming 2026 revision of the C++ standard were finalised. Our contributions are an essential part of the new standard, which enable efficient use of data parallelism on current hardware. We developed an implementation of the standard in the widely used GCC compiler and submitted it for integration. The existing standards and implementations were continued to be maintained during this time. In addition, research and development on higher levels of abstraction for C++29 is progressing [4][5].

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9.4 Activities in technology transfer at GSI and FAIR

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Introduction

GSI's technology and knowledge transfer efforts provide a gateway to its innovative technologies and knowledge developed through its scientific activities, as well as to its technical infrastructure and equipment. Additionally, it actively contributes to the translation of these advancements into practical applications for industry and society beyond the scientific community. This includes the transfer of the **scientific knowledge to society**, e.g., politics, administration, business, civil society, education, media, as well as the commercial exploitation of scientific results and technologies by industry through **technology transfer**.

Technology transfer is the process of sharing and applying research results to create **societal and economic impact**. By fostering collaboration between science, industry, and society, technology transfer enables the translation of innovative ideas into practical applications, products, and services. As part of its mission, GSI aims to accelerate the transfer of its scientific knowledge and technologies to address pressing societal challenges and create new opportunities for growth and innovation.

Organizational Integration

The Technology Transfer Department (TTR) is a staff unit directly subordinate to the Administrative Management. With currently 9 full-time equivalent (FTE) employees, including 5 FTE funded by third-party sources, the TTR is responsible for managing services and contract research, innovation management, business development, and technology marketing. Through the GSI Innovation Board, an internal committee for innovation and technology transfer, technology transfer has been even more firmly anchored within the organization.

The Innovation Board advises the management and TTR with its interdisciplinary expertise on the selection of transfer projects worthy of funding for the innovation fund, and recommends further exploitation strategies for individual patent families and inventions, taking into account technology maturity, exploitation potential, and marketability.

Transfer Strategy

In 2021, the GSI supervisory board approved a transfer strategy with defined goals. The main objective is to increase the societal impact of scientific results and technologies. The strategy focuses on technical utilization and commercial exploitation of research results and technological developments.

The GSI pursues two key goals:

- **Creating an innovation culture** by promoting awareness and understanding of transfer options.
- Optimizing and strengthening transfer activities by establishing an **effective transfer structure** and allocating adequate resources.

To achieve these goals, the GSI aims to make innovative technologies, developments, and knowledge available for use outside of their primary scientific purpose. This includes generating revenue to support further technology transfer and scientific work.

The GSI also promotes entrepreneurship through initiatives like entrepreneurship education and the Transfer Academy HAFIS. Additionally, an incentive system has been implemented to encourage innovation, including a new compensation guideline for employee inventions and a revenue-sharing model that has already led to payouts to several departments.

GSI Innovation Fund

The GSI Innovation Fund is an internal funding instrument of GSI and FAIR for technology transfer projects. The aim is the product-oriented validation and further development of market-relevant technological potential from research and development at GSI and FAIR – ideally together with an industrial partner.

Employees of GSI/FAIR can apply for funds from the fund in order to use them, for example, for further development of the product idea in prototypes, feasibility studies or also equity financing for public funding programmes with the aim of technology validation. If an industrial partner is involved in the project, it bears its own costs.

The Innovation Fund is a seed fund that is sustainably financed using financial returns from license agreements, contract research, sales and services. This return flow concept is the basis of the Innovation Fund's principle: innovative projects are funded aiming to generate returns for the researchers, the institutes and the Innovation Fund. A share of these returns is used to promote new projects via the Innovation Fund.

Since 2021, the Innovation Fund has supported fifteen projects at various stages, including feasibility studies, validation projects, and pre-startup initiatives. These projects span a wide range of fields, such as medical isotope production, LED-based laser technology, multispectral XUV microscopy, fault detection for marine and underground cables, open hardware electronics development, radiation hardness testing for space applications, and advanced biotechnology. These projects demonstrate the broad applicability of GSI's expertise and its commitment to fostering innovation in various disciplines.

Project highlights

Digital Open Lab

The Digital Open Lab at the Green IT Cube at GSI/FAIR is an IT real-world laboratory that provides a platform for research and industry partners to test and develop future technologies. The lab offers a unique experimentation field for the development and testing of energy-efficient technologies for various high-performance computing applications. This is made possible by a realistic simulation of an industrial deployment scenario, both in terms of the size of the demonstrator (multiple servers and other components) and the connections and possibilities for different operating modes (e.g., continuous operation under high loads).

The Digital Open Lab was established at the Green IT Cube in 2022/23 with funding from the REACT-EU program of the State of Hesse. The data centre capacities at the Green IT Cube are made available within the framework of scientific and industry collaborations.

Recent partnerships have been established with the Hessian Centre for Artificial Intelligence "hessian.AI" and companies like NDC Data Centre GmbH and DC Smarter. Additionally, the integrated AI Innovation Lab has become the hub of the Hessian AI Transfer Ecosystem, providing access to AI supercomputer infrastructure for over 70 companies, start-ups, and research institutions. The lab enables the development, training, testing, and evaluation of AI systems and applications.

Further scientific IT collaborations have been established with the Fraunhofer SIT, addressing research and development topics around cybersecurity and data protections particularly within AI systems.

In parallel, the Helmholtz initiative HPC-Gateway has initiated activities to support industry-driven innovation in automation and artificial intelligence. Within this framework, advanced hardware components - including NVIDIA-based systems integrated into a Rittal direct liquid cooling rack prototype - are deployed for the joint development and testing of next-generation solutions. At the same time, these activities generate valuable operational data that contribute to the continuous optimization of energy efficiency within the Green IT Cube.

Industry Beam Time

In 2025, GSI Helmholtzzentrum für Schwerionenforschung successfully conducted its first industrial beam time pilot campaigns in the field of radiation hardness testing with international partners from Germany, the United Kingdom, and the United States. The experiments, carried out at Cave A using high- and ultra-high-energy heavy ions (> 100 MeV/u up to 1 GeV/u), demonstrated the unique capability of the GSI accelerator infrastructure to reproduce realistic radiation environments for the qualification of advanced electronic systems.

STEVEN (**S**pace **T**esting of **E**lectronics with **V**ariable high **E**nergy heavy io**N**s) at Cave A/SIS-18 combines outstanding beam parameters with a user-oriented service model tailored to industrial needs. Access to this unique radiation conditions - available at only in Cave Ale chips to complex, fully integrated systems without invasive sample preparation. Complemented by dedicated user support from initial consultation through on-site execution, this framework provides a flexible and application-oriented environment for industrial radiation hardness testing of space electronics.

Building on this success, industrial beam time will be established on a permanent basis, with STEVEN, the Heavy Ion Microprobe, and the M-branch serving as key infrastructures. Dedicated day contingents have already been allocated for upcoming beam times, enabling reliable and structured access for industrial users.

Co-Creation Project

The Helmholtz Institute Jena and GSI Technology Transfer, in cooperation with Active Fibre Systems GmbH, successfully applied for funding for the project "Innovation Partnership for High-Flux EUV Light Sources in Metrology and Imaging". Following the project kick-off in 2025, the partners have established a close interdisciplinary collaboration to advance laser-driven EUV sources towards application-oriented and commercially viable solutions.

The project focuses on developing a novel approach for generating coherent, laser-like EUV radiation at a wavelength of 13.5 nm with significantly enhanced performance compared to the current state of the art. This development opens up new opportunities for applications in spectroscopy, metrology, and imaging, particularly in EUV lithography mask inspection.

By collaborating closely with industrial partners and involving end users early in the process, the project systematically integrates application requirements and market perspectives into the research and development activities. Current work addresses both the fundamental physical principles and the technical feasibility of the new EUV source concept, supported by unique research infrastructures such as the Joint EUV-XUV Technology Laboratories.

Through co-creation approaches and a joint exploitation strategy, InnoEUV aims to translate advanced EUV source concepts into robust and scalable systems, thereby accelerating the transfer from fundamental research to industrial applications and significantly reducing the time to market.

Innovative Cathode Catalyst Layers for PEM Fuel Cells

The GSI Material Science department, in collaboration with the Zentrum für BrennstoffzellenTechnik GmbH (ZBT) in Duisburg and Deutsche Gesellschaft für Galvano- und Oberflächentechnik e.V. (DGO), launched a research and development project to explore a novel application for nanowire-based structures in energy storage in 2023. The project focuses on developing an innovative cathode catalyst layer (KKS) for polymer electrolyte membrane fuel cells (PEMFC).

By leveraging the unique properties of nanowires – high surface area and porosity – the project aims to enhance electrical, protonic, and thermal connectivity within the catalyst layer, ultimately improving fuel cell efficiency and longevity. This represents a significant extension of an established GSI technology into a promising new field.

Close collaboration with industry partners and a project advisory board ensures the alignment of technological advancements with industrial needs. This project exemplifies how expertise in material sciences can be successfully transferred to new application areas, fostering innovation and addressing critical challenges in energy technology. It also supports Germany's sustainability strategy by advancing next-generation fuel cell technologies.

The project is funded by the Industrial Collective Research (IGF) funding programme of the Federal Ministry of Economics and Climate Research (BMWK).

Development of Transfer Methods

Project: OpenTransfer

Funded by the German Federal Ministry of Research, Technology and Space (BMFTR), the OpenTransfer project aims to develop strategies for transferring research results in the context of Open Science – in a joint effort with Helmholtz-Zentrum Dresden-Rossendorf (HZDR) und Leibniz-Institut für Photonische Technologien (IPHT). The goal is to create new methods for better knowledge and technology transfer, while also exploring the intersection of Open Science and transfer.

In this context, transfer refers to the use of research results outside of scientific applications, regardless of potential compensation. This can range from commercial exploitation through hybrid models to making results freely available, accompanied by business models for Open X.

At GSI, we're focusing on Open Hardware and Open Infrastructure, developing internal processes and guidelines, contract templates, and business models to facilitate the transfer of inventions. A notable example of this transfer method development is the Digital Open Lab, which showcases our efforts to create a contractual, regulatory, and financial framework for open science.

Project KST: Competence instead of Technology

Funded by the BMFTR, the KST project aims to market and exploit the technological competences of large-scale research more effectively. In this context, competence refers to the ability to analyse and solve specific problems in a defined field, combining the knowledge and experience of GSI staff, technical equipment, and organizational expertise.

The project develops and tests targeted approaches to transfer these unique competences to suitable partners in applied research and industry, with the ultimate goal of generating more and additional exploitation successes from GSI's scientific and technical potential.

Specifically, the project focuses on:

- Identifying industry partners who can benefit from GSI's competences
- Developing optimal combinations of GSI's competence offerings and industrial demand for solutions, and translating them into concrete R&D projects

Effective and efficient approaches will be implemented in processes for sustainable use in GSI's technology transfer. The processes for identifying promising competence fields and providing exploitation-oriented support for R&D projects are already in place..

Project KiTIE: Enhancing Cooperation Competence in Technology Transfer through Partner Identification and Evaluation

The KiTIE project, funded by the German Federal Ministry of Research, Technology and Space (BMFTR) is a collaborative effort between GSI TTR, the Leibniz Institute's Innovation Centre, HZDR, Christian-Albrechts-University of Kiel, and the University of the Federal Armed Forces in Munich.

The three-year project aims to develop an IT-based tool that identifies potential cooperation partners for technology transfer using patent information and patent usage data. The algorithm uses secondary data such as patent information, patent application location, and technological competence fields to efficiently identify suitable partners.

The tool will strengthen the early phase of technology transfer, where ideas are developed into viable transfer projects. It will also enable continuous optimization of the transfer process through data analysis and key performance indicators. By increasing the chances of successful technology transfer, the project will enhance the innovation capacity of research institutions.

The tool will be beneficial not only to the project partners but also to other research institutions and industry partners, who can use it to compensate for resource gaps and contribute to their own economic success. The long-term goal is to develop a software solution that can be used by all stakeholders involved in research transfer, providing significant added value.

Helmholtz Innovation Platform Hi-Acts - Successful Evaluation and Continuation

The Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions (Hi-Acts) is a Helmholtz Association-funded initiative that brings together industry and research experts to accelerate innovation in accelerator-based technologies. The project is a collaboration between GSI, DESY, HZDR, Helmholtz-Zentrum Hereon, and Helmholtz-Zentrum Berlin (HZB).

Hi-Acts provides a centralised platform for industry and medical partners to access the extensive particle accelerator infrastructure of the Helmholtz Association. The network enables knowledge and technology transfer, accelerating the development of future technologies and products. Accelerator-based technologies offer new and faster opportunities for research and development, addressing major challenges in medicine, technology, and the environment.

Following a successful evaluation on 16 September 2025 in Berlin, Hi-Acts was confirmed to significantly strengthen both cutting-edge research and industrial applications. The review recommended its continuation with unchanged funding levels.

As an “enabler,” Hi-Acts supports companies and applied research through targeted transfer measures, such as the yearly Use Case Initiatives Call. For GSI, funding amounts to €357.5k per year, of which €200k is allocated to the Use Case Initiatives (joint R&D projects with industry partners), with an option of €400k per year for Technology Labs to establish industry-oriented infrastructures.

By 2025, five Use Case projects have been funded at GSI, with a focus on industrial beamtime and increased capacity for radiation hardness testing, forming the basis for pilot industrial beamtime starting in 2025. Recent funded projects include a wind tunnel for testing cooling scenarios for servers and a prototype positioning device for upright patient treatment in hadron therapy.

Entrepreneurship Education

The Technology Transfer Department is actively involved in various knowledge transfer activities to promote entrepreneurship and innovation.

One of these activities is the participation in the Helmholtz Academy for Intrapreneurship (HAFIS), a joint initiative with KIT, FZJ, and HZDR to strengthen entrepreneurial thinking and action among researchers. The goal is to qualify approximately 25 researchers at GSI and initiate six transfer projects over a period of three years.

The TTR Department is also involved in the European technology transfer network “HEPTech” and collaborates with its partners on the digital event series “HEPTrepreneurs.” GSI continued to participate in this series, with several events held each year, including online webinars and in-person training programs. The training schools are held in Darmstadt and focus on the fundamentals of entrepreneurship, impart relevant skills, and demonstrate how science can reach society.

10. Research & developments for the FAIR Project

Head: Jörg Blaurock (FAIR & GSI)

10.1 Executive summary

Author: Emmanuel Rosi

Figure 71: View on FAIR construction Site in April 2025

During the year 2025, the FAIR project has made excellent progress towards the completion of the Early Science configuration (ES) by the end of 2027 and the completion of the First Science (FS) configuration by the end of 2028. The realization towards First Science + (CBM experiment in addition to First Science until 2028) has progressed as the FAIR Council released further procurement activities in July 2025, following the additional financing made available by FAIR Shareholders. Nevertheless, the full release of First Science + depends on the last pending contribution, which needs to be confirmed in writing so that FAIR Council can grant its approval.

The year 2025 was another pivotal year for the FAIR project as significant milestones towards the completion of the First Science configuration have been achieved. Civil concrete works for the approved buildings are completed (see Figure 71). Technical Building Installations are progressing very well, with a targeted completion by the end of 2026 and a subsequent hand-over of the facility to the Host-Lab Facility Management. The soil modelling of the outer areas is substantially completed.

On the accelerator side, the major achievement was the installation of the cryogenic components and the magnets in the Super-FRS pre-target area. The equipment was successfully installed in this very tight pre-target area due to the excellent coordination between the delivery of components, their preparation prior to installation, and the execution of the installation to their final position.

Another major milestone was achieved as commissioning activities of the cryogenic plant started in August 2025 which marks the start of the commissioning of the FAIR accelerator (see Figure 72).

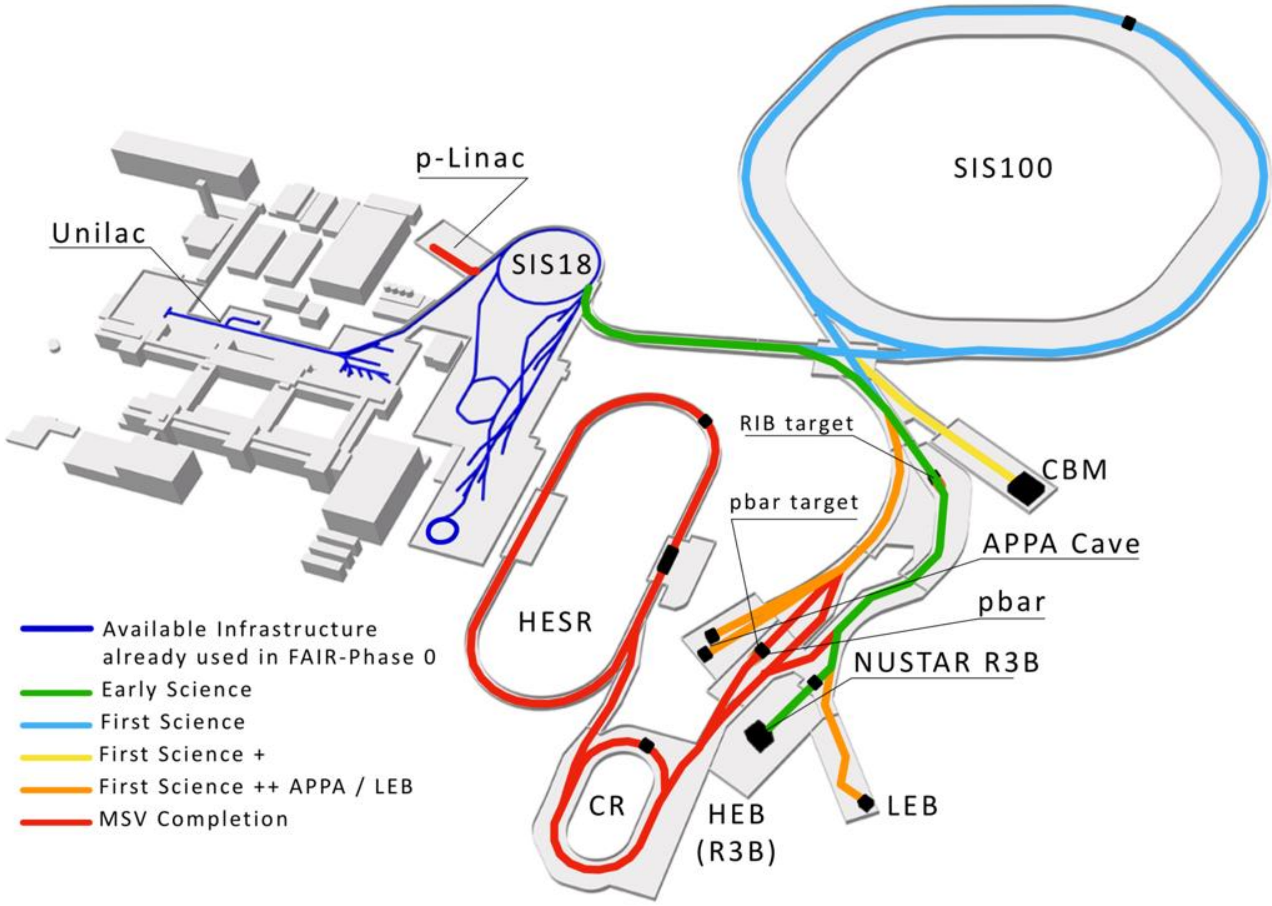

Figure 72: FAIR accelerator facilities with various entities and achievement steps

Figure 73: Overview of south area with NUSTAR building on the right, APPA building in the middle, S-FRS & Transfer buildings in the background.

Figure 74: Cryo building under commissioning.

Figure 75: Installation of Super-FRS local cryogenic branch T and sc multiplets.

Figure 76: SIS100 dipoles positioned in the tunnel

10.2 SIS18 and SIS100 Accelerator Developments

Head: Dr. Peter Spiller (GSI & FAIR)

Authors: P. Spiller, P. Bartolome, J. Blaurock, A. Bleile, L. Bozyk, O. Ciosk, T. Eisel, J. Kaether, M. Kauschke, J. Ketter, P. Kowina, A. Krämer, U. Laier, D. Lens, D. Ondreka, I. Petzenhauser, V. Plyusnin, I. Pongrac, N. Pyka, P. Rottlaender, C. Roux, K. Schulte-Urlichs, S. Sorge, K. Sugita, M. Schwickert, A. Szwangruber, P. Szwangruber, H. Welker, S. Wilfert, T. Winkler, D. Winters (GSI), M. Chorowski, A. Illuk (Wroclaw University of Technology, Wroclaw , Poland), M. Sienkiewicz (Institute of Nuclear Physics PAN, Cracow, Poland)

Significant progress was achieved in the SIS18 and SIS100 synchrotron projects.

SIS18

Within the SIS18 synchrotron, preparations for the implementation of the final measure of the GAF (*Gebäude Anbindung FAIR*) project were further advanced. The focus is on enhancing the radiation shielding in the extraction area to enable the planned high-intensity FAIR operation (Figure 77).

Figure 77: Shielding enhancement of the SIS18 extraction area by means of hematite beams.

Procurement processes for logistics and the production of hematite bars are close to completion and execution has started. In addition, the first cryogenic insert for stabilizing the dynamic vacuum during high intensity U^{28+}-operation was successfully installed and tested with beam. Major additional upgrade measures, such as a two-plane injection system, an electron lens for space charge compensation and the full implementation of cryogenic inserts for reaching the FAIR intensity goals have been proposed for the GSI accelerator road map. The replacement process for aged equipment has been started with four new power converters serving the injection quadrupole system.

SIS100

The procurement of components for a dedicated quadrupole unit test facility at the GSI STF has been launched. For the development of the magnetic field measurement equipment a collaboration contract with CERN has been signed. Integration of the quadrupole modules at BNET has been fully re-established, and the contracted integration rate of two modules per month has almost been achieved (see Figure 78). Furthermore, a new addendum covering the extended testing of quadrupole modules was signed between INFN and GSI.

The set-up of the SIS100 main power converters for the dipole- and quadrupole systems has almost been completed. The first of two commissioning runs is presently under preparation.

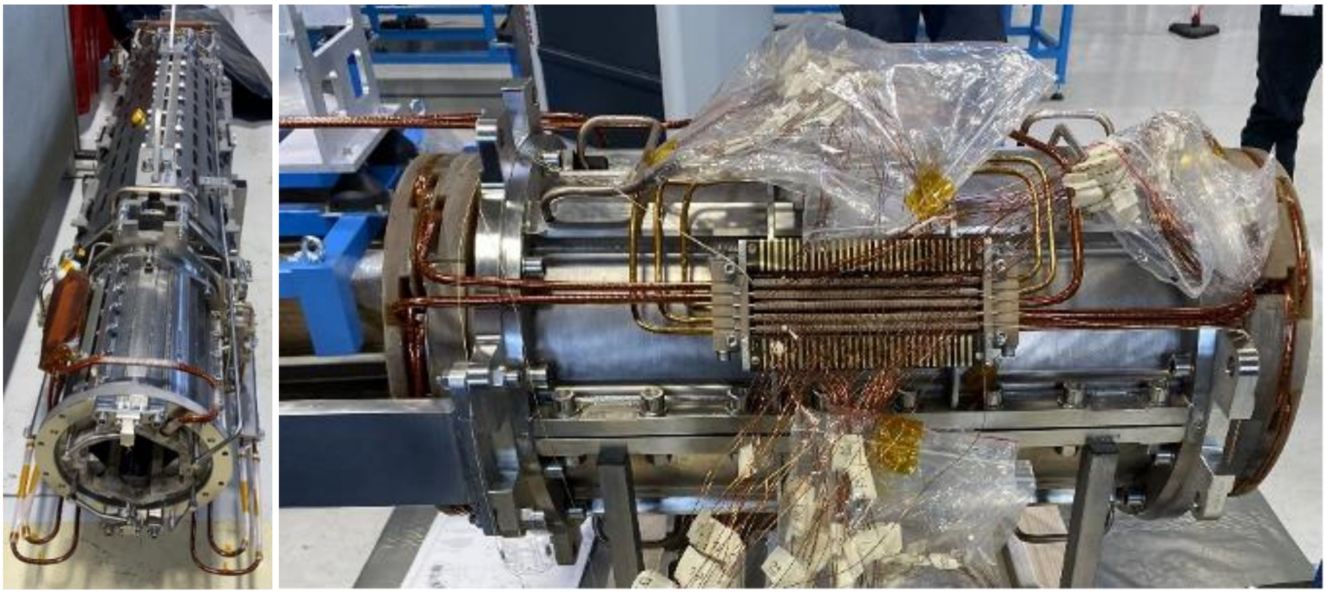

Figure 78: Left: prototype SIS100 quadrupole unit (left) and multipole corrector magnet. Right: manufactured in industry.

In terms of technical development, strategies were developed to address high-voltage cable issues in the injection and extraction kicker systems. Among other measures, the implementation of a second injection kicker module was proposed to reduce the required voltage levels. The design and drawings of the star-shaped quadrupole chambers successfully passed the Final Design Review (FDR). A thin-wall FOS chamber has successfully been produced by means of wire erosion (Figure 79).

Figure 79: FOS star-shaped thin wall quadrupole chamber.

Mirror boxes for the laser cooling facility were manufactured and prepared for installation. All chambers required for the world-wide unique laser cooler have been installed in the strait of sector 3. Radiation-hard quadrupole magnets arrived at GSI after an extended sea transport from New Zealand.

Additional progress includes the development of a procurement strategy for feed boxes 2 and 3 in coordination with WUST, with the tendering process initiated via FAIR GmbH. The FOS current lead box was successfully accepted (Figure 80)

Figure 80: FOS current lead box at acceptance test at the GSI STF (Series Test Facility).

Moreover, the welding process for process lines (pressure equipment) in the interconnection regions between the s.c. magnet modules was successfully implemented (Figure 81).

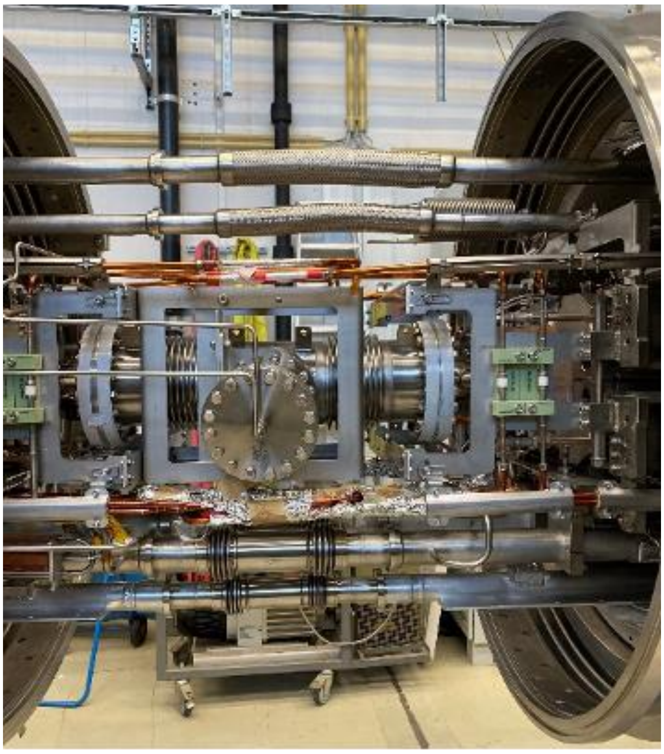

Figure 81: Dipole-dipole interconnection region with welded process lines.

Despite the progress achieved, several challenges remain. The import of quadrupole units from JINR into the European Union is becoming increasingly difficult, requiring continuous adaptation to tightening sanctions.

Furthermore, partially insufficient high-voltage strength has been observed in cold terminals. The high-voltage strength of the kicker pulse cables is also insufficient. To address these issues, immediate actions are required, including testing alternative cable types, potentially developing a new cable type, and manufacturing a second injection kicker module. These measures require prompt allocation of budget and contractual arrangements. Otherwise, delays in the delivery of the injection and extraction kicker systems are to be expected.

10.3 Division Super Fragment Separator

Head: Dr. Ralf Heinz Gebel (GSI), Dr. Haik Simon (GSI)

Author: M. V. Ricciardi and A. Wilms (GSI) on behalf of the Super-FRS Task Force

Introduction

Super-FRS components can be divided into three groups based on technological constrains. Firstly, the target region, a section of beam line which includes the production target and downstream magnets and components, surrounded by a thick radiation shielding; realizing remotely controlled components with reliable performances in a hostile radioactive environment characterizes the realization of target area. Secondly, large-apertures superconducting magnets and the corresponding powering and cryogenic systems. Thirdly, the diagnostic system, which include detectors with high-rate capability, their gas system, and vacuum chambers (also known as diagnostic chambers) at each focal plane, where detectors are housed.

Activities of 2025

For most components, R&D was concluded already in 2022. 2025 was characterised by progress in production and testing of components, and their installation in tunnel.

Target area

The manufacturing of target chamber, which embeds a rotating graphite target, a collimator, instrumentation for beam monitoring, was completed and successfully tested at factory. Due to its dimensions and weight, the chamber was delivered to GSI disassembled. The re-assembly of the chamber, including beam plugs and water-cooling system, was carried out at GSI and all functionalities were successfully tested. The target chamber was then transported to FAIR (see Figure 82) and is ready to be installed in tunnel. Also, the special alignment support on which the target chamber will be installed was produced and delivered to FAIR. Alignment supports for target-area components will be mechanically operated remotely from the roof of the iron tunnel by means of long lances. The remote mechanisms can align each component to sub-millimeter precision.

Figure 82: The Super-FRS target chamber, transported to FAIR.

The production of normal-conducting (nc) multipoles (3 quadrupoles and 2 sextupoles) (see Figure 83) was completed, the magnets were successfully tested at the factory in New Zealand. Magnets are currently shipped to FAIR and are foreseen to arrive in spring 2026.

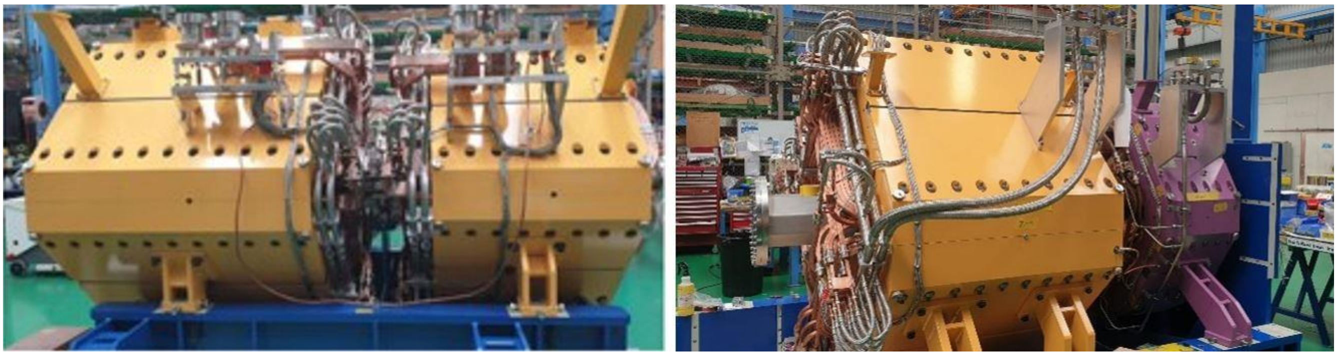

Figure 83: Two normal-conducting-magnet units: quadrupole-quadrupole (left), quadrupole-sextupole (right).

The production of nc-dipoles was completed too. Dipoles were successfully tested in the factory (see Figure 84), they were powered, and magnetic measurements were performed. Both dipoles were delivered to FAIR in Q4-2025. The third dipole, produced at BINP, Russia, is already on site.

Figure 84: A normal conducting dipole.

For the operation at high intensities, three beam catchers (BC) will catch unreacted primary beam after the target and a large part of unwanted fragments. A BC consist of a shielded vacuum chamber and removable absorber plugs. Two BC chambers were produced and delivered to FAIR (see Figure 85) and they are currently in the pre-assembly and testing phase prior to tunnel installation. The third BC will be delivered to FAIR in spring 2026.

10 special removable plugs with integrated pillow seals will be placed in-between neighbouring components to close beam vacuum and further absorb radiation. The production of all plugs was concluded and all plugs were delivered to FAIR.

The maintenance of activated components will be done in special shielded rooms (the Hot Cell) nearby the TA. Activated components will be transported from tunnel to hot cell by means of a special container (flask), which was already delivered in 2024, and whose functional test was performed in January 2025. Activated components will be deposited in the hot cell through a special entrance on the roof that can be opened and close with a special sliding lid, automatically activated once the flask is set on that. In 2025, the tender for the sliding lid was awarded, and the conceptual design was finished.

The production of all eight high-power power converters (PC) for nc-magnets in target area was completed in 2025 and all PCs were delivered to FAIR.

Figure 85: Two Beam-Catcher chambers delivered at GSI/FAIR campus.

Superconducting magnets system

All sections outside TA employ superconducting (sc) magnets and therefore operate in a cryogenic environment. For early science (ES) objectives, 35 superconducting magnet modules and their associated powering and cryogenic systems are needed.

The production of sc-multiplets (a multiplet is a unit embedding several multipoles and correctors) successfully progressed during 2025; currently 90% of the multiplets for ES are produced. Having solved a technical problem in 2024, the series production of sc-dipoles was started again in 2025; five dipoles already passed the factory acceptance test, the remaining production is on-going. Whereas multiplets integrate vacuum pipes, vacuum chambers must be inserted in sc dipoles during the pre-assembly phase. In 2025, both first-of-Series (FoS) sc-dipole chamber types (11° and 9,75° bending) were delivered to FAIR. The series production is ongoing.

Once produced, the superconducting magnets undergo cold testing (SAT tests) at a dedicated cryogenic test facility at CERN, which was established in a Collaboration Agreement between GSI and CERN that has been extended through the end of 2029. In 2025, ten additional multiplets successfully completed SAT testing, while the 2026 campaign will focus primarily on dipole magnets.

The Local Cryogenic (LC) system connects the Super-FRS superconducting magnets to the FAIR cryogenic plant. For Early Science, he system comprises five branches (T, P, M, H, and G) together with a Branch Box, a large cryogenic distribution unit supplying pre-cooled helium to the LC branches. he system comprises five branches (T, P, M, H, and G) together with a Branch Box, a large cryogenic distribution unit supplying pre-cooled helium to the LC branches. n 2025, branch T was manufactured and delivered to FAIR. Its FoS assembly — consisting of a feed box, a transfer line, and a connecting jumper — was successfully tested at the upgraded GSI cryogenic test facility (STF). Early in 2025, contracts for the production and installation of branches P and M, as well as branches G and H, were awarded to three separate industrial partners. The production of the Branch Box was also completed successfully in 2025, followed by its delivery to FAIR. he local cryogenic infrastructure further includes the Auxiliary Cryogenics Piping System (ACPS), composed of three parallel warm return process lines with a combined length of approximately 1.2 km. Production of the full ACPS was finalized in 2025, and all components were delivered to FAIR.

The industrial production of all power converters for sc-dipoles and multipoles run speedily in 2025, and was almost completed; the first batch was delivered to FAIR in November 2025. The purchasing of power converters for correctors (C3) is still an in-kind contribution of India. The purchase of long lead items was started by the Indian factory.

Finally, several contracts to produce special vacuum components (inflatable seal-gate-valve support frames, bellows) for beam-line vacuum were awarded.

Diagnostic system

Dedicated vacuum "diagnostic" chambers will be installed at each focal plane to accommodate beam instrumentation and degraders. The industrial production of 11 series diagnostic chambers is advanced; the first batch of 6 chambers passed the Factory Acceptance Test (FAT).

Most former in-kind components were developed "in-house" at GSI/FAIR campus. In 2025, having successfully tested several detectors with beam, the production of final components is ongoing. Among these, plastic scintillators, produced as replacement of time-of-flight detectors for Early Science. The series production of plastic scintillators drives was awarded to an external company. For Early Science operation, 14 fiber scintillators (see Figure 86) are employed to track ion positions, serving as a replacement for the GEM-TPC system, which will be introduced during the First Science phase to cope with the higher beam intensities expected. After the successful test of FoS detectors, the series is being produced at GSI detector laboratory. Also, the FoS dE/dx detector (MUSIC) was successfully tested with beam in 2025.

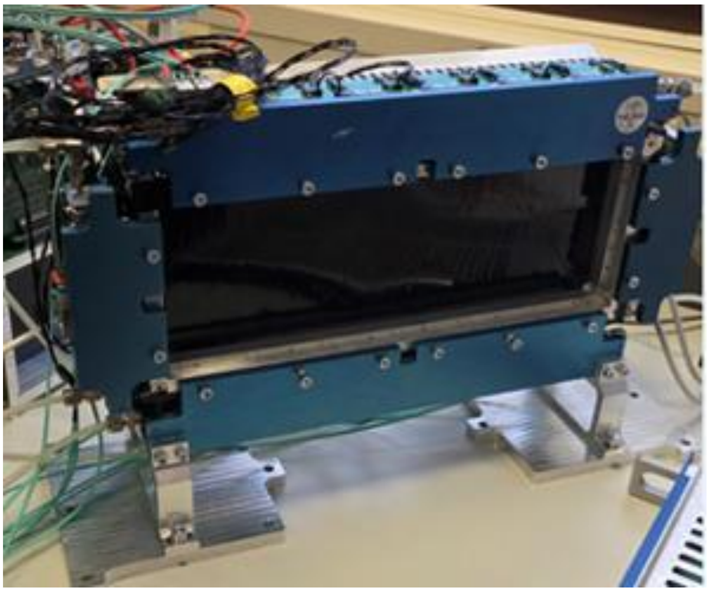

Figure 86: Scintillating fibre detector, used for particle tracking.

Pre-assembly and installation

2025 was characterised by intense activities to prepare components for installation (the so-called pre-assembly phase) and by the installation itself.

In the FAIR building, the hall reserved for the future installation of the low energy branch (the Low Energy Cave, LEC) was equipped to store and pre-assembly Super-FRS components, such as sc-multiplets and nc-dipoles (see Figure 87). Due to their high weight (about 90 ton), nc dipoles were delivery in two halves. The pre-assembly of sc-multiplets is being performed by the in-kind partner IFJ-PAN, Poland.

Figure 87: Sc-multiplets (on the left) and nc-dipoles halves (on the right) in the hall at the end of the low-energy branch.

The installation of Super-FRS started in April 2025 by placing the LC branch T in the pre-target area (the focussing section before target). After a break, during which the technical infrastructures of the building were installed, the installation of branch T was completed; successively three long sc multiplets were installed and connected to the cryogenics system. Due to the reduced space in tunnel three different concepts had to be used to install the multiplets. The first multiplet was shifted by means of a mechanical device, using rods that had to be integrated in the multiplet. Particularly challenging was the installation of the third multiplet, which is partially embedded in the iron shielding of target area. Special rails were constructed in beam-line direction on which the multiplet was placed and shifted through the iron tunnel extremely slowly, being the clearance only few centimetres. Prior to installation, the multiplet was placed on a special alignment support of the same type of those used for components enclosed in the iron tunnel in target area. Finally, the second multiplet was brought in place by air cushions transport. Although pre-target-area section is small, its installation is a cornerstone of the project. Due to the tight space and the interface with the iron tunnel the installation procedures went beyond standard methods, and it demonstrated the feasibility of all different approaches used. The installation of the pre-target-area section included also the integration of a special shaped vacuum pipe inside the concrete wall that separates HEBT from Super-FRS and other vacuum components (see Figure 88).

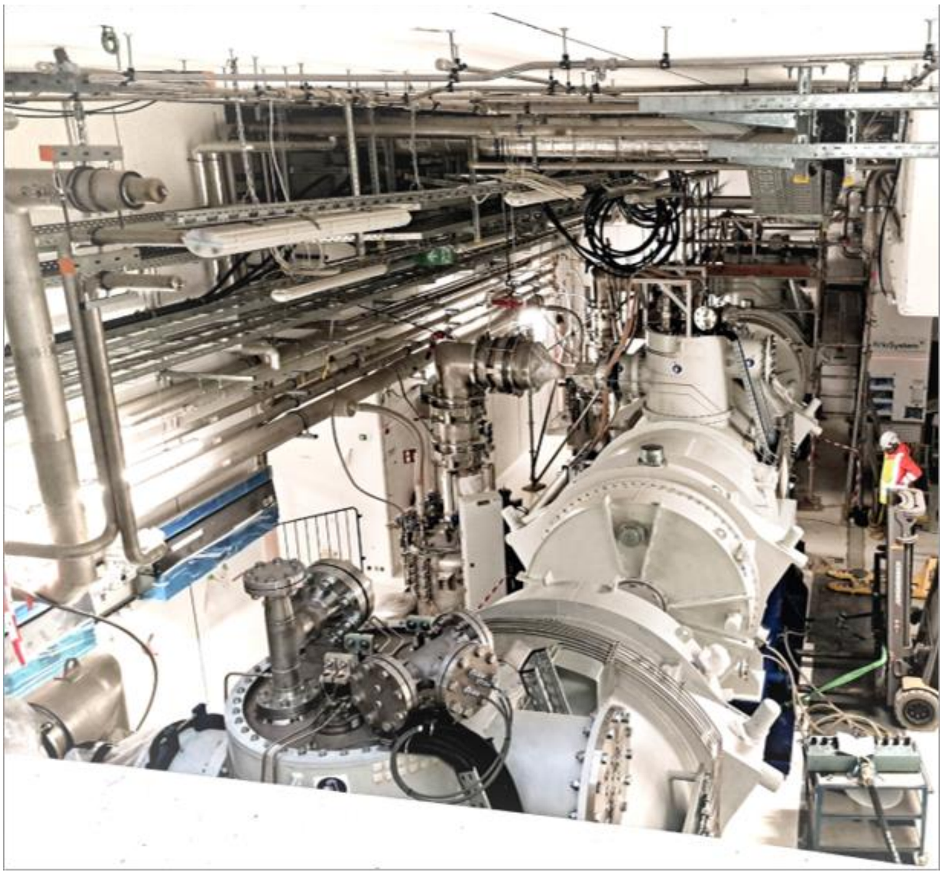

Figure 88: View of pre-target-area: local cryogenic branch T on the left connected to three long multiplets.

In addition to branch T, other important local cryogenics components were installed in 2025, like the helium distribution unit Branch Box (see Figure 89) and the warm-gas return system ACPS for all branches. Also, the capillary piping system connecting pressure sensors in the LC boxes to control racks was installed in pre-target-area.

Another important achievement in 2025 was the preparation for the installation in target area (TA). There, all components are hosted in a narrow iron tunnel acting as radiation shield, necessary in order to reduce the radiation dose rate outside the target area. There are only a few centimetres clearance between the components and the sidewalls to limit air activation in tunnel. This makes installation extremely challenging. A specialised engineering company was contracted to for the detailed planning and follow up of installation activities in target area. The installation of components in TA is expected to start in the second quarter of 2026.

Figure 89: Branch Box, local cryogenics distribution unit.

Organised workshops in 2025

In 2025 several meetings were organised by the sub-project dealing with different aspects, and/or specific topics, of installation, documentation, communication, beam instrumentation, commissioning and data acquisition. Participants from all departments and/or groups of the sub-project were involved in mostly interactive meetings, also focusing on the interplay of the different departments taking into account the different roles and responsibilities of the colleagues involved.

The meeting series of SFR started in Spring 2025 with an interactive installation workshop under external facilitation with main focus on all aspects of installation (Interactive Installation Workshop). Colleagues from all departments involved in the installation of Super-FRS participated depending on their roles and responsibilities prior and during installation. This workshop was held in an agile meeting format and had the following main goals:

- A common picture on the installation of the 1st construction phase
- A joint understanding of the roles & responsibilities during installation as well as their interplay
- A joint and agreed setup on how to work together during installation and the opportunity to clarify specific situations
- Work on specific next steps activities and open questions and plan the work across the machine sub-project and installation sub-project

A meeting with main focus on the work package of beam instrumentation (Beam Instrumentation Workshop) was organised end of April 2025 as a starting point of the intensification of the involvement of the BEA department in the Super-FRS work package of Beam Instrumentation, which also included the transfer of the work package lead.

The internally organised workshop focusing on commissioning aspects (Super-FRS Commissioning Workshop) took place end of May 2025. During this two-days event several different aspects and interfaces related to Super-FRS commissioning like planning, status reports, etc… including general aspects of sub-project commissioning were presented and discussed. In addition, the commissioning of Super-FRS as part of the overall commissioning of the machine was raised.

End of October 2025 a two-days off-site interactive workshop under external facilitation took place dealing with different aspects of currently ongoing installation and the continuation of the envisaged installation sequence mainly based on the concept of "Installation along the beamline". Definition of functions and roles, which have to be "on-board", as well as the interaction/interplay of different groups during the installation phase were discussed as well as specific topics of current importance. The second day of this workshop was held in a Barcamp format with focused discussions on different aspects, selected based on priorly given short presentations of the respective topics by different groups. This chosen meeting format introduced one kind of agile meetings, foreseen to be implemented in near future into the currently existing agile meeting structure of the sub-project.

A Super-FRS DAQ workshop was held at the end of November 2025, organized on-site by the work package leaders primarily involved in the DAQ activities of the Super-FRS sub-project. It marked the final major event in the 2025 Super-FRS meeting series. Colleagues from different departments involved in R&D and/or production related to the Super-FRS DAQ activities participated with valuable contributions. Several discussions rounded off the clear agenda of this event.

10.4 Division Commons

Head: Stefan Menke (GSI & FAIR)

Authors: Dr. Marcus Schwickert, Dr. Andreas Reiter, Dr. Anne Seidel, Elena Nickchen, Dr. Christina Will, Horst Welker, Dr. Martin Eibach, Carolin Englert, M. Flath, Dr. Frank Hagenbuck, Dr. Carsten Mühle, Lukas Urban, Dr. Jennifer Wenzl, Dr. Stefan Zeller

Department Beam Diagnostics (BEA)

Authors: Marcus Schwickert and Andreas Reiter

Accelerator operations and operation of the infrastructure support

The BEA department focuses in 2025 on continuing and completing a number of long-term beam diagnostic upgrade projects. In preparation of the move to the new FAIR Control Centre (FCC), several diagnostic systems of the UNILAC were being renovated in the past years. One important milestone in 2025 was the finalization of the refurbished macropulse selector system (MAPS) for the readout of all beam current transformers in UNILAC. All outdated hardware components were replaced by modern µTCA acquisition modules. In addition, new FESA software and user interfaces were implemented for seamless integration into the accelerator controls system. After successfully passing tests with beam during the wet-run in June 2025, all beam tests are from then on in routine operation. Figure 90 shows the electric cabinet with the new data acquisition system (left) and the new graphical user interface for beam intensity measurement of two consecutive beam current transformers (right).

Figure 90: Electronic rack with MAPS data acquisition hardware (left) and MAPS graphical user interface (right).

Thus, by 2025, all beam diagnostic projects required for the move to the new FAIR control centre have been successfully completed. In order to study the longitudinal beam parameter in detail, novel Feschenko-type bunch-shape monitors (BSM) are being prepared for installation in UNILAC. Also, two BSMs, located inside UNILAC and transfer channel, respectively, will be used for optimizations of beam matching and multi-turn injection into SIS18.

In SIS18, the Ionization Profile Monitor (IPM) was significantly upgraded through major improvements to its software, including full FESA integration and the addition of new measurement capabilities. Also, the work on the digital camera readout for the high-energy beam transport lines (HEST) has made significant progress and meanwhile all scintillating screens in the HEST are read out with the CUPID camera readout system. Additionally, the main parts of HEST particle counters, like e.g., photo multiplier tubes and plastic scintillators, have been modernised to enable more precise intensity measurements.

Research in accelerators, detectors, electronics and IT

In 2025, BEA department performed several machine experiments to test and optimize new detector systems. Several machine studies using the GSI-built fast Faraday-cups (FFC) with 10 GHz bandwidth were carried out. For FFC readout a dedicated graphical user interface was developed to provide online display of measurement data and to control of all device parameters. Figure 91 shows an example for a bunch shape measurement using an FFC.

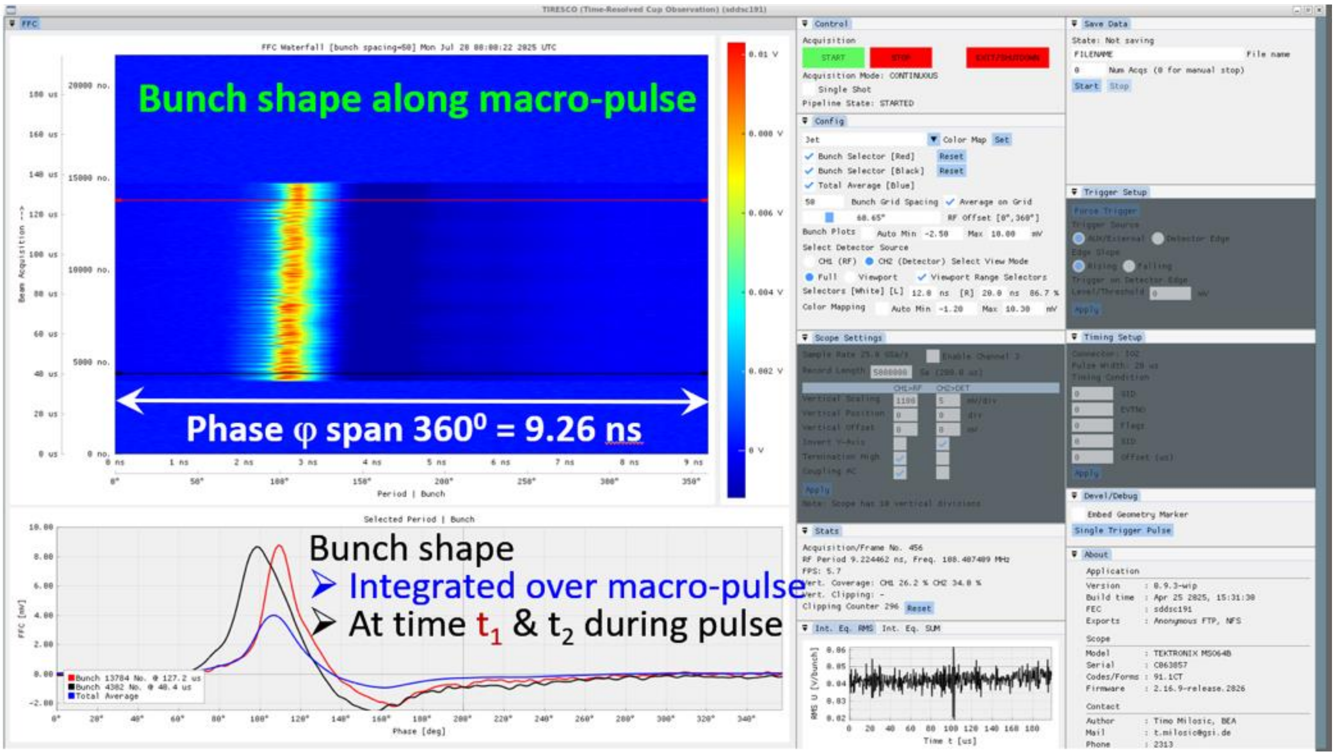

Figure 91: Graphical user interface for FFC bunch shape measurements.

In addition, during the 2025 beamtime, OTR prototypes (optical transition radiation) were integrated into the HTP beamline to measure beam profiles and to perform single ion counting. These monitors successfully captured heavy ion beam profiles at intensities as low as 1E6 Uranium ions per spill. Furthermore, the experiments demonstrated that these radiation-hard OTR counters can effectively detect single ions, with pulse rise times significantly faster than traditional scintillator detectors. This research is carried out in close collaboration with University Liverpool.

Moreover, the new spill optimization system (SOS) for SIS18 was used for the first time in routine machine operation during 2025, and the effects of the SOS system for spill smoothing were again studied in more detail. A new version of the graphical user interface was developed and the requirements given by the operations team were successfully implemented.

To facilitate future developments, a collaboration agreement between the beam diagnostic departments of CERN and GSI was signed in 2025. This agreement covers development tasks that both laboratories have in common and now formalizes the long-standing collaboration in the field of beam diagnostics: It covers a large spectrum of diagnostic work packages, ranging from the development of cryogenic current comparators for beam intensity measurement, studies on luminescence monitors, and collaborative work on ionization profile monitors, to FESA integration of several diagnostic devices, as well as common developments on SEM-grid monitors, the development of hardware and analysis methods for beam position monitors, and joint development work on special instrumentation for measurements of slowly extracted beams.

Research and developments for the FAIR project

With the delivery of Programmable Logic Controller (PLC) hardware and software for pressurised air drives in spring 2025, the last components of the Slovenian in-kind contributions arrived at FAIR. Site-acceptance tests were carried out in the following months. After successful completion of this development phase, the final acceptance documents of the Slovenian in-kind contribution were signed by all partners during a formal ceremony in October, hosted in Ljubljana by the Ministry of Higher Education, Science and Innovation.

In 2025, further infrastructure equipment was delivered including all high voltage systems for HEBT and SIS100, as well as most parts of the detector gas supply system. The gas mixing station was installed in supply building G0704A in autumn 2025, while the external gas storage area is still under construction.

Software and integration tests for detector systems were continued during the 2025 beam time with focus on fast extracted beams. For beam position monitors, a new gating algorithm based on time-of-flight and precise knowledge of the kicker timing now enables an automated selection of the beam pulse for position analysis. The performance of the new HEBT resonant transformer hardware was also verified during beam tests. Series production for head amplifier and interface box is under preparation. Further measurements with slow extraction focused on measuring beam profile at low intensities during a study with the multichannel charge sensitive AWAGS amplifier [1].

Most of the 22 beam diagnostics assembly groups for Early Science are ready for installation. A major milestone was thus achieved by the assembly of 45 multi-wire proportional counters / ionization chambers (MWPC/IC).

38 MWPC/ICs have already passed quality acceptance, and the final batch is expected in February 2026. For Early Science, a few detectors, SEM monitors and plastic scintillators are still to be completed and will be installed in the second half of 2026.

Both Cryogenic Current Comperators (CCC) detectors for Early Science are under construction for non-intercepting intensity slow extraction monitoring [2]. Cryostat and liquefier for the 2nd CCC were ordered in 2025 with delivery is scheduled in Q2/2026. The collaboration with the University of Jena has further succeeded in securing federal BMFTR funding to advance the development of a compact CCC for storage rings, while also strengthening the partnership through increased CERN involvement, which is again focused on accelerator transfer line application. This new funding includes a new PhD position that will be filled in January 2026 to support the BEA R&D team.

Several projects for the stage First Science have been continued. Version 4 of the current-to-frequency converter IFC4 has been developed with improved linearity in the most sensitive 100 nA range and the required modification for the external power supply for the SIS100 tunnel. Finalisation of series production up to 400 units was shifted to Q1/2026. For the SIS100 beam stoppers, the pneumatic actuators and special stopper blocks (see Figure 92) were delivered. Manufacturing of Schottky pick-ups is nearing completion. Meanwhile, design work on the BTF exciter (Beam Transfer Function exciter) has commenced. A BTF exciter is used to apply a small, controlled oscillation to the particle beam. By observing how the beam reacts to oscillation, it is possible to extract important beam parameters.

Figure 92: Gold-plated stopper block for SIS100 beam stopper

Department Engineering (ENG)

Authors: Dr. Anne Seidel, Elena Nickchen, Dr. Christina Will

The digital mock-up (DMU) of the GSI & FAIR is a course CAD model of the entire accelerator. It consists of a “shell geometry” of machines, buildings and technical infrastructure. It is intended mainly for installation purposes and makes it possible to answer questions like: Can a new part be mounted? Is there enough space to move it around? Is there sufficient space for a worker to carry out the necessary installation works? Are escape routes big enough once the mounting is complete?

The DMU group is generally needed to document changes to the existing GSI machines and during the installation of the new FAIR accelerator. Without doing that, the available CAD data does not represent reality with the required level of quality.

Because some GSI buildings and their technical installations were constructed in the 1970's and are therefore not yet included in the model, planning renovations is significantly more complex.

Moreover, there are even discrepancies between the model and reality for the new FAIR accelerator, e.g. caused by deviations between first planning and realisation or building settlements during the first time after construction.

For all these reasons, 3D scanning can be a powerful way to mitigate the above-described issues and to facilitate planning and documentation.

For this purpose, a Faro Focus S70 laser scanner is deployed. It uses a near-infrared laser and a phase difference method for measuring distances. In addition, it captures HD images of the scenery [3]. Reference objects like spheres or printed marks are placed in the environment, and their positions are known very precisely. During post-processing, the reference objects are registered by the software FARO scene, and all measured distances and images are used to create a coloured point cloud. This consists in millions of 3D data points that are spatially referenced to a zero point. This zero point is the same for all 3D data used at GSI and FAIR. The measured data can be visualised using a software (Scene2Go) that enables a 360° coloured walk-around, so that you can move around the room as if in a computer game. One can also measure distances between surfaces there.

Figure 93 shows an example of scan data visualization with Scene2Go of an area in the "Super Fragment Separator" (Super-FRS) beam line in FAIR. Clicking on the bubbles that are displayed in several places makes the user "jump" to a new place. On the walls left and right, one can recognize the visual black-and-white marks for referencing.

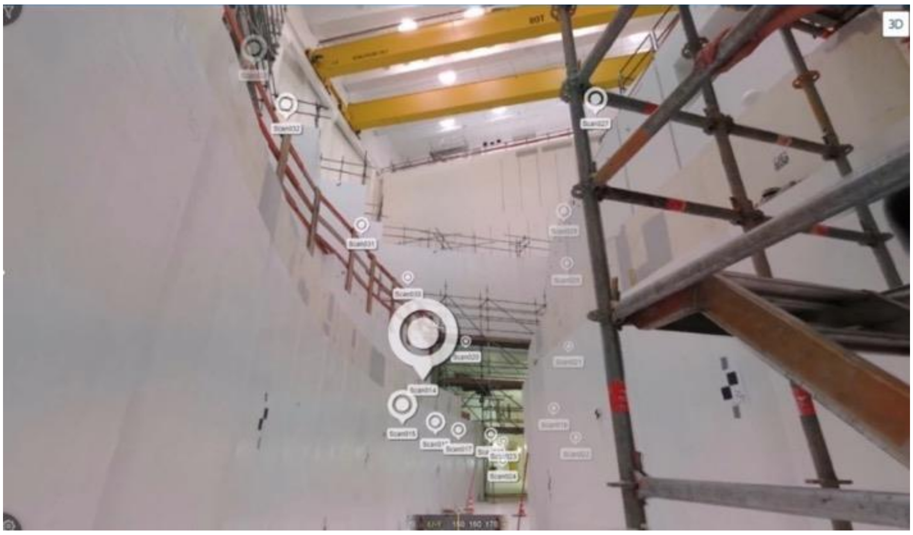

Figure 93: Visualization of coloured point cloud of "Super Fragment Separator" (SFRS) in Scene2Go

By loading the spatially referenced point cloud into the CAD software CATIA, deviations between measured coloured points and the CAD model can be detected by visual comparison. This software used for a coordinated model of buildings, infrastructure and machines is NavisWorks. Implementing the point cloud allows measurements between points and model. An example is given in Figure 94. It shows a view into the NavisWorks model of the "High Energy Beam Transfer" (HEBT) segment of the FAIR accelerator. The solid components on the right, which look rather massive, are CAD representations of machines which are not yet installed. The photorealistic environment and installations show the measured point cloud. A human silhouette can be positioned and moved around the scenery.

Figure 94: Superposition of CAD model and coloured 3D scanned points in the "High Energy Beam Transfer" (HEBT)

A further possibility is to generate a meshed model in the software Kisters where points are connected to create small triangular surfaces. This model can be superimposed to the CAD model (see Figure 95), so that besides visual comparison and distance measurements, sections through both geometries can be generated.

The software Scene Modeler enables reverse engineering. At the moment, the application at GSI/FAIR is still limited to deriving the geometry of flat surfaces (walls, infrastructure like racks) and pipes. The use of reverse engineering is planned to be extended in the future. Integration of the scanning data into the GSI/FAIR data process is strived for, so that automatic use in maintenance is made possible. Conceivable applications could be to use scanning data to automatically extract geometrical data by recognizing standard components, or automatic identification of standards that must be fulfilled. An integration of scanning data into Virtual Reality remains to be investigated.

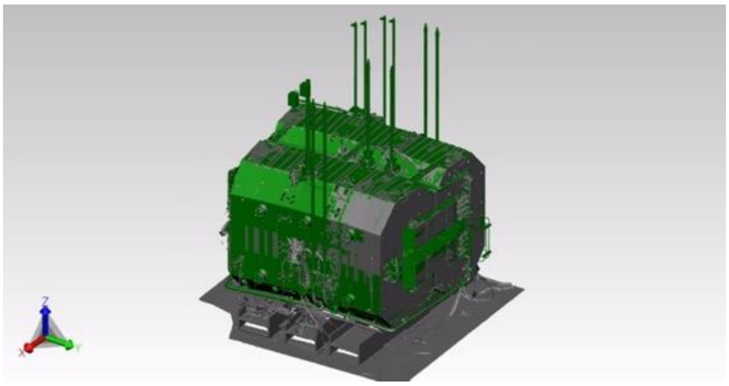

Figure 95: Superposition of meshed scan data (grey) and CAD model (green) of a normal conducting magnet in Kisters

Department Electric Power System (EPS)

Author: Horst Welker

Machine cable management and User Cable

The Cable Database continues to be the main tool for collecting and maintaining the user cable data.

Latest cable data are regularly provided to Fair Site & Building (FSB) for the planning of cable routing and the global laying of user cables. Same data are used for the design of machine trays and for the cable installation process by EPS.

A regular and fixed communication is established between the companies for cable installation, for cable routing, FSB and tray designers, as well as with all machine representatives responsible for cables.

After contracting the company Electricity EOOD, Bulgaria, in 2022, user cables laying is continuing in 2025 in coordination with the machine installation. Up to now approx. 870km (10.100 cables) were laid. See Figure 96 and Figure 97.

Figure 96: Cable laying in SIS 100

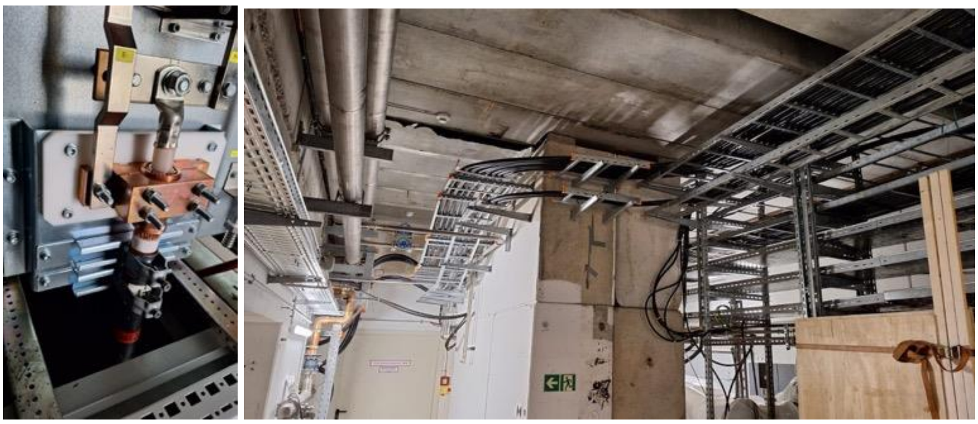

Figure 97: Coaxial cables connected in EPS racks

Machine tray montage has started in SIS100 and also in the beamline T1S1 (connection GSI-FAIR); see Figure 98.

Figure 98: Machine trays and final laying in T1S1 (connection GSI-FAIR).

Department. High Energy Beam Transport (HEB)

Authors: Dr. Martin Eibach, Carolin Englert, M. Flath, Dr. Frank Hagenbuck, Dr. Carsten Mühle, Lukas Urban, Horst Welker, Dr. Jennifer Wenzl, Dr. Stefan Zeller

In 2025, activities for the high energy beam transport system (HEBT) focused on ongoing procurements, the re-procurement of ex-Russian components as well as the pre-assembly and installation in the tunnel and in the supply rooms, in close collaboration with the sub-project Site Management (SMG).

After the assemblies of beam line section T1S2 were transported into the transfer tunnel in 2024, the realization of the Early Science beam line from SIS18 to Super-FRS and the preparation of the First Beam Event (FBE) in the first section planned for December 2026 are in full swing.

In summer 2025, the installation of the beam line section TSX1 in the central crossing building started. The installation of the section T1S1, which connects to the existing facility, began in the GSI transfer hall (TR) in October 2025. In addition, all power converter, beam instrumentation, vacuum and controls racks were installed in the HEBT supply rooms in building G0704A in 2025.

Furthermore, the detailed planning for the commissioning of HEBT Early Science and First Science sections and for the FBE was carried out.

Magnets

For the HEBT magnets, all project phases from contract closure to installation had to be covered in parallel:

1. Upcoming procurements: As all previous stages had been approved, the preparation of procurement for First Science++ was initiated.
2. Contracting and design progress: The option for the missing First Science+ magnets was exercised, the contracts were closed, and approximately one third of the design work has already been completed.
3. Design completion and production status: By the end of 2025, the design of all Early Science and First Science magnets contracted to Sigmaphi (France) was completed. Production is ongoing, taking longer than originally anticipated. All Quadrupole 2 magnets are now expected at GSI at the beginning of 2026.
4. Delivery and installation activities: All steerer magnets supplied by Partzsch were delivered in early 2025 and have mostly been equipped with vacuum chambers. Magnet pre-assembly and tunnel installation were carried out in two beamline sections.
5. Commissioning preparation: With the First Beam Event and Early Science approaching, the development of commissioning strategies for all beam line magnets was initiated.

Power Converters

All power converters for 159 HEBT quadrupole and 93 steering magnets manufactured by the Indian company ECIL have been successfully tested, and shipped to FAIR.

Moreover, 40 of 53 power converters for dipoles (14 types) and all eight power converters for quadrupoles (2 types) contracted with the company Jäger Elektrotechnik GmbH (Germany) have been successfully tested and delivered to FAIR. Due to their high power and size, the remaining 13 pulsed power converters will be connected to the 20kV supply system and have to be assembled directly in the building. The associated 20kV transformers have already been delivered, and seven of them have already been installed in building H0719A.

The assembly of the corresponding power converters is planned to start in Q2 2026.

In addition, the installation of all 45 power converter racks in building G0704A has been completed. Their commissioning is planned to start in Q2 2026 with priority given to the First Beam Event. The installation of all racks for 144 power converters in building H0719A is planned to be started at the beginning of 2026.

Vacuum chambers

In 2025, all vacuum chambers required for Early Science were delivered. All magnet and pumping chambers for Early Science (ES) have been installed in their respective assembly groups and are ready for installation in the tunnel.
In addition, six pumping chambers and 13 round chambers for quadrupole and steerer magnets for First Science Plus (FS+), which were awarded as an option to the Italian company SAES RIAL, were ordered. The pumping chambers were delivered before the end of 2025, while the delivery of the magnet chambers is scheduled for February 2026.
Furthermore, the supply of nine Quadrupole 12 chambers (three branching chambers and six oval chambers with bellows) for FS and FS+ was contracted in 2025 with Revol TT (Slovak Republic). In addition, a contract with the Italian company TEES for the delivery of 124 beam pipes was also signed in 2025. These beam pipes are required to complete the vacuum system for all FS and FS+ beam lines. Both procurements are carried out jointly by FAIR and the Nuclear Physics Institute of the Czech Academy of Sciences.
Due to quality issues identified with the dipole chambers supplied in 2025 which could not be handled by the contractual partner, the decision was taken to initiate a new tender for these chambers. The corresponding contract is planned to be concluded at the beginning of 2026.
All further components required for the vacuum commissioning of a beam line were procured and assembled in 2025. This includes mobile pumping stations, leak detectors, helium bottles, mobile control racks for standard components, and compressors required for the operation of gate and edge valves within the beam lines.

Special Installations

The complete series of collimators, which will be deployed behind the charge stripper at the exit of SIS18, has been delivered by the Italian company Comeb Srl. All units were integrated into their respective assembly groups and commissioned as a standalone system. Further units, which will be deployed behind SIS100, are in production.
The design and production of the HEBT charge stripper was successfully awarded to the Polish company PREVAC. The Kick-Off of this project will be in Q1/2026.
All HEBT SI assembly groups for the ES beam line sections have been prepared and are ready for tunnel installation.

Special Stands

Kraftanlagen Heidelberg awarded Baumann MV with the production of the large support frame in building H0705A. The start of production is planned for Q2 2026 in order to allow installation of the large support frame in September 2026 in compliance with the overall HEBT installation plan.
The GSI Mechanical Integration Team completed the second contract of the modular stands, which were manufactured and delivered by BLEICHERT in August 2025.
The design of the overall vacuum stands is under responsibility of GSI's design office. After completion of the design of the pumping chamber stands for FS and FS+, a call for tender was launched in December 2025. Finalization of the design for the remaining stands is planned for summer 2026 followed by a production start in Q3 2026.

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11. Accelerator Operations and Development

Head: Dr. Ralph Aßmann (GSI)

11.1 Executive summary of Business Area Accelerator Operations and Development

Author: Ralph Aßmann

Our division is responsible for operating, maintaining and developing the GSI accelerator complex that provides heavy ion beams for thousands of users. This is one of the world's leading accelerator infrastructures for nuclear physics and its many applications in fundamental research on matter, in oncology, in radiobiology, in materials and in high density matter, amongst others. In addition, we operate the central workshop and the technology laboratory, which include mechanical machines, 3D measurements, the brazing oven and GSI's Galvanic workshop, one of the world's largest of its kind. The staff of our division provides the resources for operating and developing our facilities, including filling mandatory roles of machine coordinators and safety responsibles.

Safety Record

The safety of the public and of our personnel is the highest priority in all our activities. The shutdown projects and the beam operation in 2025 were carried out without any relevant safety-related incidents. This illustrates the high safety standards that guide our work, but also the great care and excellence of the experts responsible for accelerator operation and for our technical facilities.

Beamtime 2025 with Improved Availability

Figure 99: The Beam Time Retreat 2025 took place on 20 and 21 August 2025 in Kranichstein, Darmstadt, close to the GSI research centre.

The 2025 beamtime for users started on 5 Feb 2025 and ended on 6 July 2025. Beam operation continued until 1 August 2025 for machine experiments and tests of the new controls system ("controls wet run"). In 2025 we operated the accelerators for a total of 6 months, the longest period since 2014 and about 1 month longer than in 2024. This prolonged operation is a big step towards full beam operation (8 months of accelerator operation). The long 2025 user run achieved an availability of 83,9 % beam on target which is above our operational goal of 80% and the best value since 2012. In particular, it is well above the 2024 result of 75% availability. This success was supported by a clear repair policy and helped by the fact, that no major breakdowns occurred. Various technical issues occurred but could be temporarily mitigated such that the run 2025 could continue.

The user run was followed in July 2025 by an engineering run (1 week – 20 machine experiments) and a controls wet run (2 weeks – tests of the FAIR control system). With the new FAIR control system, the beam was accelerated and transported from the ion sources through the UNILAC and through the SIS-18, from which it was successfully extracted. This is an important achievement towards the fully digital GSI operation, as required for operation from the new FAIR Control Centre FCC planned after Summer 2026.

The results from the user run and beam operation in 2025 were reviewed in a very vibrant beamtime retreat held on 20.-21. August 2025 in the nearby Jagdschloß Kranichstein and Stiftung Hessischer Jägerhof (see Figure 99). A list of to do actions was defined for work until the planned controls wet run in February 2026 and the users beam time in October 2026. The beamtime retreat also discussed the technical roadmap for the facilities and required modernizations. Slides and summaries of the 2025 beamtime retreat are available at: https://indico.gsi.de/event/22284/overview.

The yearly ACC workshop was held at GSI on 20 October 2025. The workshop brings together all staff in the business area ACC. The workshop outlined the path to an integrated accelerator campus for FAIR and GSI. It provided an overview of current ACC activities and an outlook to the next years. The workshop was followed by the traditional informative exchange between all ACC employees and their leadership.

Accelerator Upgrade Projects and Shutdown Work 2025

The accelerator upgrade projects in ACC made good progress in 2025. The pulsed gas stripper project in the UNILAC was used in routine operation ahead of planning during the full beamtime 2025, providing excellent beams and lessons for next improvements. The Post-Stripper Upgrade (PSU) project ("new Alvarez2.0 Linac for the UNILAC") was executed following the project plan with both tanks and drift tubes being copper plated to specifications and being assembled. The PSU project status and its present budget commitment of almost 16.3 M€ was presented to the GSI supervisory body and a further 9.3 M€ until 2030 were approved, inside the total project volume of 35 M€. The PSU project includes certain modernization projects for the Linac RF system and progress was made on the procurement of a 150kW solid state amplifier. The Injector Controls Upgrade (ICU) project made major progress in the upgrading of the UNILAC control system upgrade to FAIR standards. This upgrade was successfully tested in a second test run with beam ("wet run") for three weeks after the beamtime in July 2025. As mentioned before, this first controls test with UNILAC and SIS18 together was fully successful. In August 2025 the old GSI control system was then permanently put out of operation, a major step for our laboratory. Finally, a new project for modernizing the old access control ("Türverriegelungssystem TVS") of the UNILAC was strongly advanced. A prototype of a new system was specified, constructed and successfully tested.

The GSI accelerator shutdown work started on 2 August 2025, immediately after the end of the beamtime and was performed successfully until the end of 2025. This long shutdown, interrupted by a controls wet run with beam in February 2026, was planned to last until August 2026. In addition to various accelerator tasks, its planning involves the renovation of the experimental hall (EH) and the upgrade of the radiation protection shielding of SIS18.

Helmholtz Programme-Oriented Funding (PoF), Hemholtz Meetings, Connection to Universities in the Rhein-Main Area

The ACC division strongly contributed to the required reporting and the evaluation of the accelerator facilities and accelerator R&D (ARD). The ARD program for the PoF-V period was defined and resources accordingly planned until 2034. A technical roadmap for the modernization of the GSI accelerator facilities was prepared and discussed during various meetings and reviews, including the PoF evaluation in April 2024. The PoF evaluation results strongly supported the planned accelerator R&D but also pointed out the need for modernization efforts in the GSI accelerator complex, as listed in the new technical roadmap of the GSI accelerators.

GSI, including the ACC division, hosted the 11th annual meeting of the program Matter and Technologies from November 3rd to November 5th (lunch-to-lunch). The meeting was complemented by a lively and inspiring MT Student Retreat for students and young postdocs (November 5th - November 6th). The connection to the universities in the Rhein-Main area was optimised and emphasised by the accelerator R&D plans defined in the contexts of Helmholtz ARD and the GSI technical roadmap. The appointment of the ACC division head to a W3 professorship at the Goethe University Frankfurt institutionalised this stronger connection, complementing similar appointments of GSI accelerator specialists at the Technical University Darmstadt and the University Mainz.

The division coordinated the report on the POF4 achievements in Accelerator R&D (LK1), in Accelerator facilities (LK2) and for GSI in-kind work on FAIR (LK-FAIR). The preparation of the reports Volume I and Volume II was supported and its timely submission was assisted.

Performance Committee: Technical Roadmap of the GSI Accelerator Complex

The performance committee, that had been implemented in February 2024 by the ACC division, completed its work on a technical roadmap for the GSI accelerator complex in the year 2025. The technical roadmap, that was agreed by the technical experts in the performance committee, defines a prioritised modernization program for a total of 39.5 M€ investments, spanning from 2026 to 2034. Those investments are targeted to address obsolescence of components (80% of invest), limited improvements in intensity reach (15% of invest), reductions in setup times (4% of invest) and improved sustainability (1% of invest). About 50% out of the total invest volume is reserved for UNILAC modernization projects, in particular in the UNILAC RF system with its major components from 1974. The technical roadmap was widely presented to internal meetings, the directorate, the WTR and the Joint Scientific Council GSI&FAIR. A special international FAIR MAC review of a technical roadmap for the GSI accelerators took place at GSI from June 25-27, 2025. A 72-page document was produced in German and in English, including detailed lists of needed and prioritised measures for the GSI facilities, motivation, prioritization criteria, POF recommendations, outcome of the special MAC Review, spending profiles, deliverables, and a detailed risk register. This document was submitted and presented to the 115th GSI supervisory board in November 2025, where it was adopted as reference document for required modernization work.

Supporting and Preparing FAIR

The ACC division continued in 2025 its support activities for the completion of the FAIR project. This included machining of FAIR components at the GSI mechanical workshop in our division and major support for the welding work for FAIR installation. The FAIR control system, including the project of the UNILAC controls upgrade, was continually steered and reviewed for adequate process and prioritization. The ACC division provides the leadership for FAIR commissioning, including definition of commissioning plans, budget planning and control. The second commissioning workshop for FAIR was organised successfully in 2025 with participation of external experts from CERN, DESY and ESS. A first beam event was planned for December 2026 and the required work was advanced with high priority in 2025 already. In preparation of FAIR commissioning and a unified GSI-FAIR accelerator complex the Accelerator Controls (ACO) department joined the ACC division. This structural change was implemented in a very smooth way, successfully leveraging synergies between activities in the ACC division and the ACO department.

11.2 Accelerator operation

Beamtime Report, Operations & Availability

Head: Dr. Stephan Reimann (GSI & FAIR)

Authors: M. Vossberg, O. Geithner

Operation

The beamtime 2025 (see Figure 100) was successfully executed until end of July 2025 and started with a preparation block on January 13th for the UNILAC RF conditioning. Subsequently, the facility's devices were commissioned with and without beam. At the end of the commissioning block, there were operator-training shifts including the preparation for the upcoming physics experiments. The physical beam time within the FAIR Phase 0 began on February 3 and was planned for 127 days, which was about 30% longer than in recent years. The physics run ended on July 6, followed by a short block for machine studies and a three-week test of the new UNILAC control system. On August 1, the entire facility was shut down for the 2025/2026 shutdown works.

During the beam time, a total of 12 different ion types with varying energies and charge states were accelerated, and 65 different experiments were available. The physical beam operation was divided into two large sections that occurred before and after Easter. In the first section, a two-beam operation with Calcium beam from the EZR source for UNILAC experiments in X8 and Y7 began, concurrently there was a silver beam, followed by a short Krypton block from the high-current source for M1-3 as well as for experiments at ESR, HTC, HTD, HTP, and FRS. Subsequently, there was a three-week block with Calcium beam from two different sources, for M1-3, X0 at UNILAC, and for experiments at HTA, HTC, HTD. The Gold beam was also slowed down in the ESR and provided for HITRAP and CryRing. At the end of the section before Easter, there was also Lead beam from the high-current source for experiments at FRS and ESR.

Due to staff shortages, no experiments were offered during the Easter holidays. To maintain the accelerator's conditioning level, the UNILAC-HF remained in operation. This time was also used for minor repairs and maintenance works, as well as to prepare settings for upcoming experiments.

After Easter, experiments with gold beam for M1-3 and X0 from the Penning source and for HADES from the high-current source continued. In the next block, Bismuth beam was offered in parallel with Iron beam for X6, HTD, as well as for FRS and ESR. ESA experiments with iron beam also took place successfully this year. From mid-May, the EZR source was switched back to Calcium beam to support experiments at X8, Y7, and materials research at M1-3 until the end of beam time. Parallel there was also Carbon beam for various experiments at HTA, HTC, HTM, HTP, and FRS followed by was a short Argon block for HTC, ESR, and FRS. Toward the end of the beam time, there was an intensive 25-day Uranium block. In this block, materials research experiments at M1-3, HTA, HTC, HHT, FRS, as well as at ESR and CryRing via ESR could be supplied. Throughout the post-Easter block, there were repeatedly additional internal CryRing experiments with Hydrogen, Lithium, Oxygen, and Iron beam.

Overall, the beam time was successfully conducted with 84% beam-on-target, compared to 75% in 2024 (IMG1). An improvement in beam-time planning provided dedicated setup times, longer blocks with the same ion, better parallel operation concepts, and compatible experiments. Improved documentation in OLOG and CryRing operation, as well as more stable and efficient operation. Collaboration between shift operations and the machine team also improved; good preparation of SIS18 patterns by the machine team contributed to the improvement. The control system was optimised, making operation significantly more stable. The experiment requirements led to a very tight beam plan, with an average parallel-operation factor of about 3.0. This required constant new settings/adjustments to the equipment, especially from May to July, when up to 7 experiments were supplied simultaneously. The very ambitious and dense beam schedule meant that the majority of operators had to be scheduled in rotating shifts over a period of more than five months without interruption. This was only possible because the operators did not take any vacation during this period and thus ensured that the Main Control Room (MCR) was manned the entire time.

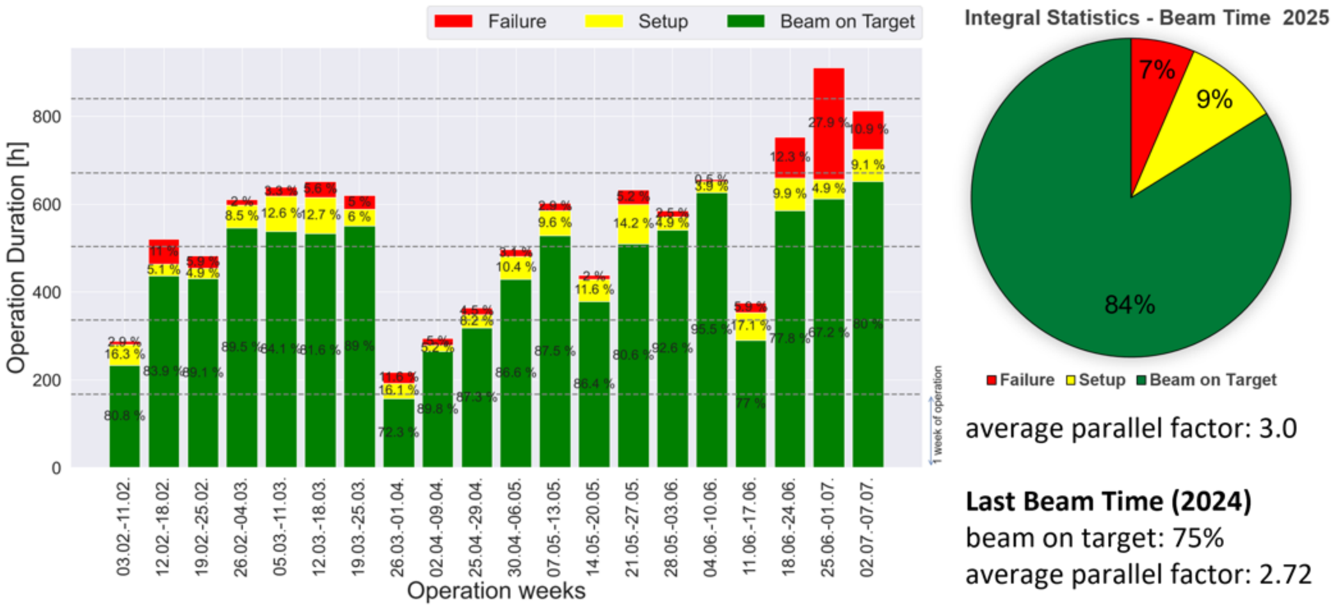

Figure 100: The diagram (left) shows the different event durations during the experimental beamtime 2025.Each bar represents a period of one week, starting from the date shown on the x-axis and ending on the following Sunday. The colours green, yellow and red depict beam on target, setup, and interruption respectively. In the case of experiments running in parallel, the times are summed up. Each of the horizontal dashed lines marks a one-week period, so that the parallelism factor can be read on a weekly basis from the height of the bar. The parallel factor over the entire experimental beamtime is 3.0. The right picture shows the overall availability for the experimental beamtime 2025.

Availability

For the year 2025, the total operating time was 10,950.1 hours, consisting of 9,157.2 hours of beam on target, 991.9 hours of setup time, and 801 hours due to failures. The parallel operation factor increased to 3.0 - a substantial rise compared to the previous beam time. This reflects the higher number of experiments being conducted in parallel and the more intensive use of the accelerator facility.

The analysis of failure statistics and their root causes was continued throughout 2025. As in previous years, the recorded failures were assigned to the correspondent specialist groups and reviewed after the beamtime to identify both technical and organizational areas for improvement.

Availability reached its highest level in the past decade, with 84% of beam on target time, 7% on setup, and 9% attributed to downtime. Combined with the elevated parallel factor of 3.0, this resulted in a significant increase in effective user beamtime compared to previous operational periods.

The downtime analysis revealed top 3 failures with noticeable impact on experiments:

- LINAC RF systems, particularly the A2 transmitter,
- vacuum components, such as roots pumps and their associated subsystems,
- weather-related disruptions.

Improvement actions will focus on the controls, operation and BAU area. These include the implementation of an on-call system for industrial control systems (SCADA), additional automation of operational procedures, improvements in archiving and monitoring of KPIs, and systematic tracking of target and actual machine parameters. These measures are complemented by planned repair and refurbishment activities on critical hardware components. Furthermore, the installation of a protective roof structure above the SIS18 transformer units is currently under discussion in order to reduce the impact of severe weather conditions on operation. Together, these actions aim to stabilize operation in the time of rising complexity and preparation for FAIR commissioning.

Shutdown Report

Head: Dr. Stephan Reimann (GSI & FAIR)

Authors: M. Klich, M. Müller

After the successful beamtime the long shutdown from August 2025 till August 2026 started. This long period is caused by two activities, first the renovation of the experimental hall (EH) and second the upgrade of the radiation protection shielding of SIS18. The entire power system in EH will be refurbished in 2026 and during the replacement of the hematite bars there will be a time slot when it is not possible to work under the open ceiling.

Another activity is the testing time required for the further development of the new UNILAC control system before the beam time 2026. This test with beam will be done in January and February 2026 at UNILAC and SIS18. The challenge is to have these parts of the machine ready for beam before this test.

Therefore, the shutdown period is divided into two parts, one until the test and the other after the test, so all activities needed to be divided between these two time slots. Figure 101 shows an overview of the entire shutdown period.

FAIR

This is the first time GSI and FAIR will have real interference because the connection between them will be built during this shutdown. At the start of the shutdown, collisions between new FAIR components and existing GSI accelerators were discovered, necessitating adaptations to the GSI's existing TE line. The remodelling of the existing facility and the installation of FAIR must be carried out in close coordination. The FAIR connection is the priority, which results in delays for other projects that depend on the same resources.

UNILAC

In the first part of the shutdown at the Alvarez A2 in UNILAC the gold seals between the tank-parts have been exchanged and the vacuum leak at the buncher BB5 has been fixed. Vacuum commissioning will be finished in the beginning of 2026. Smaller repairs were carried out, such as fixing damaged profile grids, replacing defective valves and repairing water leaks. The access control system (TVS - *Türverriegelungssystem*) modernization is progressing, with the goal of completing it later in 2026. The work on the Alvarez A3 tank cap and drift tube, scheduled for 2026, is being planned, and preparations for the maintenance of the triplet of HLI inter-digital cavity (IH) are underway.

SIS18

At SIS18, the electron cooler cathode was exchanged and heated to resolve the strange behaviour observed at the end of the previous beamtime. The conditioning will be done right before the control system test. The installation of the main power cable has been completed ahead of schedule. However, in 2026, the multi-channel plates (MCPs) at the Ionization Profile Monitor (IPM) will be exchanged.

HEST

Work on the CUPID (Control Unit for Profile and Image Data) update for HEST began as planned but was interrupted by the remodelling of TE line for the FAIR integration. This remodel has taken priority, resulting in delays to HEST's schedule. The space adjustments necessary for the FAIR connection have been progressing slowly, as the remodelling of TE1 is a complex task.

In 2026 it is planned to finish the CUPID upgrade, exchange the foil in the stripper to ESR and check the stripper in TH4.

ESR

The activities at ESR for the experiment preparations and the repair of the IPM are planned for 2026. The repair of the septum from ESR to HITRAP was postponed due to a shortage of resources, which resulted from the prioritization of TE line remodelling for the FAIR project.

FRS

The main activities at FRS are upgrading the stepper motors and using the open ceiling due to the replacement of the hematite bars to remove the robot at S1 and replace it with a crane.

CRYRING

At CRYRING@ESR the development of the 14.5GHz ion source is ongoing and the vacuum conditions at section YR08 were checked. If there will be enough resources the scraper in YR07 will be repaired in 2026.

HITRAP

In HITRAP, the ion source operates when the control system is available, and the radio frequency (RF) system undergoes testing during dedicated periods throughout the shutdown.

Civil construction and infrastructure

From mid-September to mid-November the two main cooling water circuits downstream transfer channel (TK), KS01 and KS02, and some ventilation systems were shut down due to upgrade of the cooling towers on top of the building BG.

In March 2026 it is planned to continue the exchange and refurbishment of several fire protection dampers which started in the shutdown 2025 and in May 2026 it is planned to exchange the low voltage main distribution (EA).

Outlook

The second part of the shutdown will be challenging due to the postponed and added activities. Therefore, a review of the upcoming activities regarding their feasibility will be conducted.

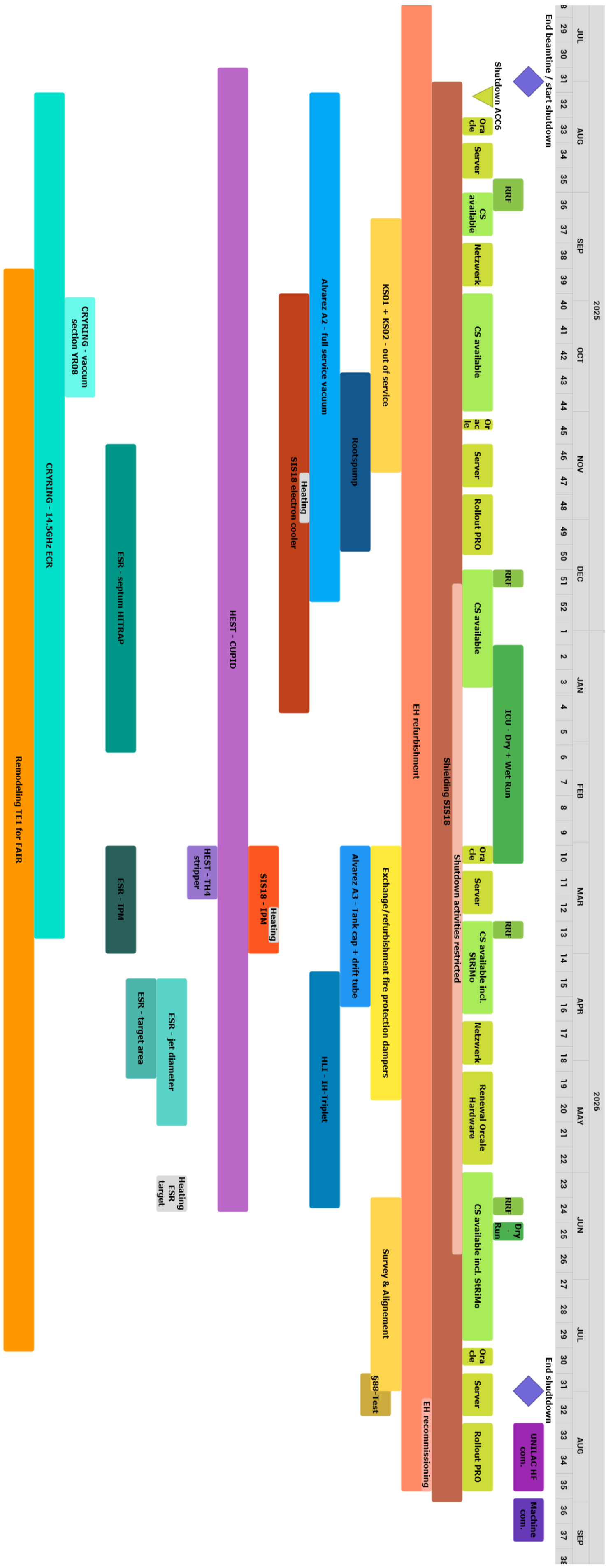

Figure 101: Overview Shutdown 2025/2026. See the electronic version of the Annual Report for zooming on details.

GSI Ion Source Operation

Head: Dr. Ralph Hollinger (GSI)

Authors: R. Hollinger, A. Adonin, A. Andreev, R. Berezov, M. Galonska, J. Mäder, F. Maimone

The ion sources department provided various types of ions for a physics run (see Table 3), as well as for machine studies and for tests of the new control system (wet run) in 2025. The high current ion sources, including Multi Cusp Ion Source (MUCIS), Cold or Hot Reflex Discharge Ion Source (CHORDIS) and Vacuum Arc Ion Sources (VARIS) from Terminal North, the Penning Ionization Gauge (PIG) ion source from Terminal South and the ECR Ion Source (ECRIS) from the High Charge State Injector (HLI) were supplying the UNILAC in parallel operation. The table below shows the ion species delivered to the accelerator. Representative values of intensities are the analysed beam currents in front of the High Current Injector HSI-RFQ and of the HLI-RFQ, respectively.

Ion species	Duty cycle*	Intensity (RFQ/emA)	Ion source	Duration (days)
$^{12}C^{3+}$ + $^{4}He^{+}$	CW	0.13	ECRIS	9
$^{40}Ar^{8+}$	CW	0.1	ECRIS	31
$^{48}Ca^{10+}$	CW	0.1	ECRIS	71
$^{56}Fe^{2+}$	5 Hz / 1 ms	0.25	PIG	11
$^{197}Au^{8+}$	25 Hz / 3 ms	0.05	PIG	33
CH_3^{+}	2 Hz / 0.45 ms	2	MUCIS-1990	14
$^{40}Ar^{+}$	2 Hz / 0.5 ms	9	CHORDIS	10
$^{78}Kr^{2+}$	2 Hz / 1 ms	4	MUCIS-2010	7
$^{107}Ag^{2+}$	1 Hz / 0.5 ms	3.9	VARIS	20
$^{197}Au^{4+}$	1 Hz / 0.4 ms	4	VARIS	36
$^{208}Pb^{4+}$	1 Hz / 0.4 ms	4.2	VARIS	13
$^{209}Bi^{4+}$	1 Hz / 0.5 ms	4.5	VARIS	12
$^{238}U^{4+}$	1 Hz / 0.45 ms	10	VARIS	25

Table 3: Ion species delivered to the accelerator during the physics runs. The ECRIS was in operation to provide $^{40}Ar^{8+}$ ion beams for machine experiments, $^{48}Ca^{10+}$ ion beams for the superheavy element programs and $^{12}C^{3+}$ + $^{4}He^{+}$ mixed ion beams for the biophysics programs. *: Duty cycle from ECRIS is always CW but the UNILAC provides at most 50 Hz / 5 ms

In 2025, the superheavy element research groups at GSI carried out three experimental campaigns using the calcium-48 (^{48}Ca) ion beam provided by the CAPRICE ECRIS. Each campaign ran continuously for several weeks, requiring careful management of the source material. For each campaign, the evaporation oven was loaded with about 300 mg of calcium, an amount estimated to be sufficient for the entire run. To support the process, three tantalum liners were used, one for each campaign, playing a key role in improving material efficiency. The results were remarkable since the intensity of the $^{48}Ca^{10+}$ beam reached values of up to 140 µA, while maintaining good stability throughout the campaigns.

The Carbon-Helium mixed ion beam was extracted from the ECRIS using CH_4 with helium as a support gas with the aim of studying a promising new option for image and range-guidance in carbon ion therapy, which is crucial to explore its full precision potential and clinical benefit. The main highlight of the mixed ion beam delivered in 2025 was the successful production of variable ratios of carbon/helium in the beam. The source and low energy beam transport were tuned to A/Q=4, with the aim of producing approximately 130 µA of $^{12}C^{3+}$ and a variable current of $^{4}He^{1+}$. The source was operated for weeks prior to beam time to achieve clean, stable working conditions. Different intensities of helium ions in the beam were investigated by changing the concentration of the helium support gas. Most measurements were performed with a 'low', 'medium' and 'high' helium concentration setting, with exact ratios determined post-hoc. The 'low' setting corresponded to a goal of ≤10% helium ions in the mixed beam and the 'medium' helium concentration setting was aimed to yield a ≤20% helium ion concentration, which would be the approximate maximum regarding the additional dose in the treatment (≤1% of the RBE weighted target dose). For the imaging runs, performed in May 2025, in addition, a 'high' helium concentration was used, where the ratio of helium ions was increased to about 50%. A 5% to 7% oxygen contamination was observed in all measurements which has to be removed in future experiments.

The Penning Ionization Gauge (PIG) ion source successfully delivered $^{56}Fe^{2+}$ beams for material research, HTA, ESA, HFS and biophysics program, achieving the required performance in terms of beam stability, operational reliability, and a source lifetime of up to 120 hours with the required repetition rate. Beams of $^{197}Au^{8+}$ were supplied for material research over a total of 33 days, organised into two operational blocks. At a repetition rate of 25 Hz, the source lifetime ranged from 40 to 60 hours, depending on the extracted beam intensity.

Furthermore, the PIG ion sources provided $^{40}Ar^{2+,4+}$ and $^{48,50}Ti^{2+}$ beams for the operator training, as well as $^{40}Ar^{2+}$ beams for the "WET-RUN" phase to verify the performance and reliability of the new control system.

Operation of high current ion sources (MUCIS, CHORDIS and VARIS) at Terminal North was generally stable, delivering high performance without notable issues. The entire 14-day block of CH_3^{+} operation for ACC and BIO was performed using a single source (MUCIS-1990) without any filament replacement. The maximum requested ion beam current in front of the HSI-RFQ was

2 emA. This allowed 1 emA of C^{6+} beam to be achieved at the end of the transfer channel (TK), corresponding to $9{\cdot}10^{10}$ particles within a 90 µs pulse. The calculated average gas consumption during methane operation was approximately 0.6 litres per day.

A ^{78}Kr ion beam was provided by the MUCIS-2010 source for HFS and ESR experiments. A beam current of 4 emA of $^{78}Kr^{2+}$ was achieved in front of the HSI-RFQ, enabling 1 emA of $^{78}Kr^{34+}$ ($1.6{\cdot}10^{10}$ particles in a 100 µs pulse) to be reached at the end of the transfer channel. Enriched ^{78}Kr gas was used. The average gas consumption during operation was approximately 0.1 litre per day.

A three-week block of ^{107}Ag for accelerator experiments on SIS and ESR, as well as for HFS and S-FRS detector tests, was carried out using VARIS. A high current beam of up to 3.9 emA of $^{107}Ag^{2+}$ ions was delivered. Cathodes made of natural silver were used for operation. The natural abundance of the ^{107}Ag isotope is 52%. Despite the small mass difference between the silver isotopes (M=107 and M=109), clear separation of ^{107}Ag in front of the HSI-RFQ was achieved through careful beam focusing optimization in the LEBT and appropriate slit settings.

Operation of ^{197}Au at Terminal North was divided into two blocks: 23 days in March and 13 days in April and May. The first block can be considered a highlight of the beam time 2025. The entire 23-day block was completed using a single VARIS source without any service interruption. A beam current of 4 emA of $^{197}Au^{4+}$ was delivered to the UNILAC for further acceleration. The source was operated in request-mode, allowing us to perform the entire block with only 7 cathodes. The average lifetime of a single cathode exceeded 48 hours.

Operation of two other heavy elements, ^{208}Pb and ^{209}Bi, mainly for experiments at the ESR was also stable and demonstrated high performance of the ion sources. Since the production of highly charged ions (4+) requires the generation of high plasma density in VARIS, operation with Au, Pb and Bi is accompanied by a notably increased number of electrical breakdowns in the extraction system and, consequently, a higher number of extraction power supply failures. To improve reliability and fault tolerance, the extraction power supply was upgraded after the beam time 2025 to withstand higher peak currents. As a result, the maximum peak current during the beam pulse that the extraction power supply can tolerate before switching off has been increased from 466 mA to 770 mA.

The longest block operated with high current ion sources in 2025 was the uranium block: 25 days for a physics run and 7 days for machine studies. A beam current of 10 emA of $^{238}U^{4+}$ was delivered in front of the HSI-RFQ from VARIS to serve various high energy experiments at SIS, ESR and CRYRING. In addition to the physics run, a high current $^{40}Ar^{+}$ beam was also provided from Terminal North by a MUCIS-1990 source for operator training and testing of the new control system (wet run).

Operation and Challenges of the CRYRING @ ESR Facility

Head: Dr. Frank Herfurth (GSI)

Authors: F. Herfurth, Zoran Andelkovic, Wolfgang Geithner, Nicolas Kehl, Gleb Vorobyev

In 2025, the low-energy storage ring facility CRYRING@ESR successfully delivered a variety of ion beams to experiments using both its local injector and the GSI accelerator chain including the Experimental Storage Ring (ESR). The achieved intensities were close to or even surpassed the requested or expected intensity. All approved experiments nevertheless obtained data. A very flexible handling of the schedule and often shorter than scheduled setup times did in general deliver additional measurement time. Beam conditions consistently met or exceeded the requested quality, especially concerning beam cooling. A notable example is the deceleration of D^{+} ions to energies below the nominal injection energy, followed by stable storage and electron cooling at only 90 keV/u. Studies of nuclear reactions at this low energy have never been conducted before in a storage ring.

Figure 102 summarizes the 2025 schedule in more detail. As can be seen, the beam setup periods marked in yellow are typically shorter in the logged real beam time data than in the preplanned schedule. Exceptional efforts by the operators and the machine experts allowed for speeding up considerably of many of the setup procedures. The U^{91+} run was an exception due to a faulty calibration of an imaging detector. This was compensated for by extending the experiment into the machine experiments time frame.

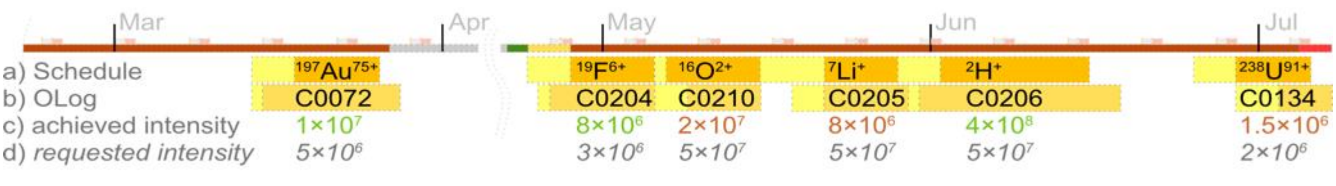

Figure 102: Overview of the beam time at CRYRING@ESR in 2025: a) Scheduled periods with the requested ion species; b) Time periods when the beam was delivered as documented in OLog, the accelerator logbook; c) Achieved intensity: green when above or red when below.

Three out of six beams exceeded expectations in terms of intensity, while three beams were not delivered with the intensity requested in the experiment proposal. The challenges for Li^{+} and O^{2+} from the local source-injector were identified and communicated to the experimentalists early on and were accepted, however, the challenge for U^{91+} was somewhat unexpected. Not only the setup was considerably delayed and complicated, but also the transmission never reached the 30% achieved in earlier runs.

Figure 103 below plots a comparison of transmission and intensity for the two runs in 2025, when beam from the ESR was delivered to experiments in CRYRING@ESR. While it was possible to maintain transmission of Au^{75+} ions at around 30%, or at least close to 20%, for extended periods, it never exceeded 15% in the uranium run. The measured transmission compares the number of ions stored in the ESR just before extraction with those stored in CRYRING@ESR right after injection. Therefore, it includes extraction efficiency as well as transfer and injection efficiency. The parts are difficult to separate; however, it is known that the transmission in the High Energy Beam Transfer line (HEST) depends strongly on the transverse beam shape, which in turn depends strongly on the conditions just before extraction. Despite efforts to control this the key mechanism behind a good transmission and the reason for the differences observed in Fig. 2 have not yet been identified. Additionally, the time available to achieve proper transmission is very different. This is because, for the gold beam, only one deceleration step in the ESR was used resulting in at least 1.5 times more shots per hour of Au^{75+}ions than for U^{91+}ions.

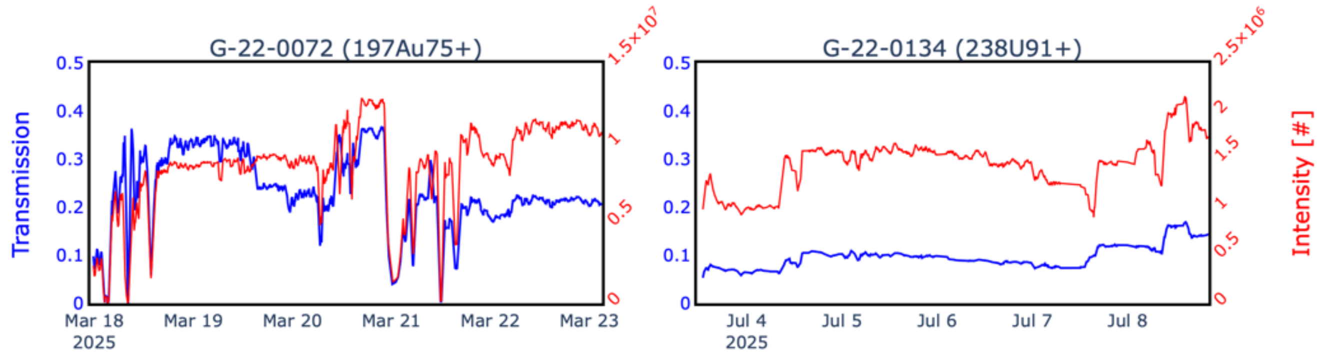

Figure 103: Comparison and analysis of transmission for the two runs with beam from ESR to CRYRING@ESR. The left plot shows in blue the transmission of beam stored in the ESR to beam stored in CRYRING@ESR and in red the intensity right after injection in CRYRING@ESR for $^{197}Au^{75+}$. The right plot shows those values for $^{238}U^{91+}$. The data has been smoothed using a running average of 100 and 50 shots, respectively. Data with no beam from the ESR, as well as data with transmission due to measurement noise above 1, has been skipped.

The efforts that went into improving the vacuum system of the electron cooler section finally paid off. Replacing the cathode, carefully testing it, and repeatedly baking the entire cooler section resulted in much improved pressure. Background of measurements with the electron cooler as a target hence was reduced to a level that the experiments with F^{6+} and O^{2+} ions concluded successfully.

In 2025 the installation of the 14.5 GHz ECR ion source previously installed at Frankfurt University proceeded. However, due to their age, many components were no longer fit for extended operation. As the permanent magnet-based sextupole also broke, the source will not be available for user operation in 2026.

HITRAP Progress Report and First Experiment

Head: Dr. Frank Herfurth (GSI)

Author: Z. Andelkovic

GSI scheduled two beam time periods for the HITRAP facility in 2025: one in February and one in early March, with about a 10-day pause in between. Before the first period, which was dedicated to commissioning, the team focused the detectors to analyze the beam leaving the cooling trap. Shielding against external fields was added to an essential detector to mitigate the deflection of the decelerated ion beam by a charged MCP. A retarding field energy analyser was also incorporated to examine the ion charge states and energy distribution that result from storing and potentially cooling the ions. Finally, in collaboration with the material research department of GSI and TU Wien, respectively, the HITRAP team prepared a LiF sample for irradiation with slow HCI in order to benchmark performance and a target ladder for subsequent experiments. Electromotors were mechanically integrated into the first four diagnostic chambers and equipped with FESA classes to operate remotely. The goal is to integrate all 14 diagnostics and motors at a later stage.

The commissioning beamtime was done with $^{107}Ag^{45+}$ and took about two weeks. The results showed a very encouraging reproducibility of ion deceleration all the way to 6 keV/u and transport to the trap. The beamtime was used to perform the first simultaneous storage of online ions and electrons, which did not produce conclusive results. The nights were used to irradiate the LiF sample and a polycarbonate foil in order to estimate the achieved fluence by subsequent chemical track etching. The commissioning also revealed several issues that need to be addressed during shutdown:

1. In contrast to 2011, the IH exhibited a lower deceleration efficiency and a different energy dependency, as illustrated in Figure 104. The underlying cause has not yet been identified, but it may be due to a large momentum spread of the incoming ion bunch and/or by a defect in the IH.

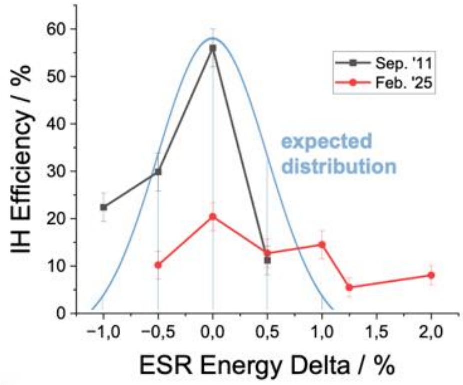

Figure 104: Distribution of the IH deceleration efficiency as a function of energy detuning, as achieved previously and in the last beamtime.

2. The non-decelerated components of the beam prevent stable injection of the slow beam into the trap, most likely by secondary electrons created upon impact. To counter this effect, an intermediate beam block for the fast beam component shall be designed, constructed and installed.
3. Upon switching the capture electrodes on the ion trap, a prohibitively large noise was generated on the neighbouring detectors. This made detection of small ion signals impossible, especially close to the trap after ion extraction. This issue will be addressed by implementing a more robust cable shielding and relocation of the electronics.
4. The quadrupole triplet and steerer unit of the IH developed a water leak with an increasing leaking rate. At the time of last use the rate amounted to about 320 l/day. As the unit is essential for proper operation, it is unknown if this issue contributed to the low deceleration efficiency of the IH.

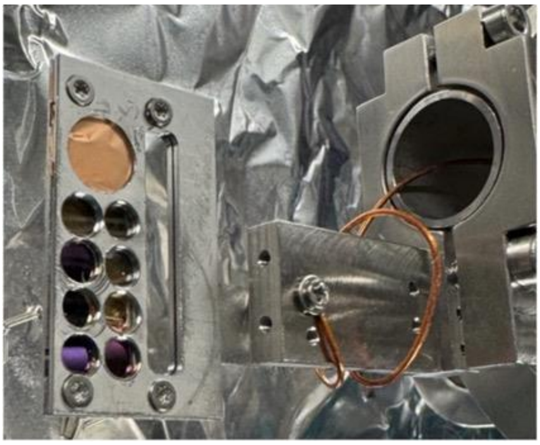

Figure 105: The sample ladder for the G0057 experiment at HITRAP.

The experiment beamtime was conducted with $^{197}Au^{79+}$ and lasted about 10 days. The research group from TU Wien and the University of Duisburg prepared a target holder together with the DEC team, as shown in Figure 105. The teams assembled the target during the break between two beamtimes, followed by a baking period. With the help of the main control room operators, after the extraction from the ESR the beam setup from 4 MeV/u to 6 keV/u took about five shifts. This provided additional shifts for the experiments, amounting to about 20 in total, versus the originally planned 16 shifts.

The intensity of the decelerated ion beam was measured by deflecting it onto an off-axis micro-channel plate detector, so that the fast beam components were able to propagate basically unperturbed. The signal was calibrated by employing the same measurement scheme for locally produced ion beam of $^{40}Ar^{16+}$ at 2 keV/u. The micro-channel plate was used both in electron multiplier (amplifier) mode and in Faraday-cup mode, where the incoming charge is collected on the first plate and discharged over a post-amplifier. Extrapolated to the signal obtained during the beamtime, this procedure indicated $6(2)\text{x}10^4$ ions per shot, or a total fluence of $6(2)\text{x}10^7$ ions per cm^2 deflected to target ladder over the course of the experiment.

Beside this calibration procedure, the local ion source was used to deliver ions to the HITRAP experiments and to test various detector configurations for the offline operation of the HITRAP cooling trap. Electron cooling and ion detection via cyclotron excitation were successfully reproduced. These activities required stable beam production and transport through the local beamline, including the cooling trap and a branch towards experiments. To this end, the FAIR control system was expanded to include the voltage power supplies and detector setups of the beamline sections GTR6 and GTR7. The DEC team used these new features to conduct first semi-automatic optimization of ion transport using genetic and Bayesian algorithms. Voltage settings for up to 58 elements were optimised while observing either the integral or the maximum of the signal on a chosen detector, yielding distinct results. Both algorithms converged within several hours and for the most part either matched or exceeded the results achieved by experienced operators. While the expansion of the beamline's functionality was demonstrated in principle (e.g., alternating ion delivery to two beamline branches and timed operation of the power supplies) further development was halted until the FAIR control system is fully implemented.

Outlook to the upcoming experiments

The result of 2025 demonstrates the feasibility of the planned experiments at the HITRAP facility, provided the current commissioning momentum can be maintained. This holds especially with respect to the control system features, available manpower and scheduled commissioning beamtimes. The DEC team prepared and submitted internal reports to discuss and implement appropriate strategies to address both the issue of resources and the feasibility of future experiments.

Subject to control system availability, the HITRAP local ion source will continue operating to supply ions for cooling trap development and new experimental setup. To support this, the beamline will be extended next year to add a new dipole bending magnet and a third branch leading to the new laser laboratory.

ESR operation

Head: Dr. Bernd Alfred Lorentz (GSI)

Authors: *B. Lorentz, R. Hess, R. Joseph, C. Krantz, S. Litvinov, M. Steck, U. Popp, J. Rossbach, A. Sherjan,*

The ESR beam operation time 2025 was with 143 days again longer than in the previous year, slowly approaching the goal for full operation with 200 days per year. It covered the time from 05.02.-06.07.2025. Beam was delivered to 10 physics experiments, two at HITRAP, three at the CRYRING@ESR facility, and 5 internal to ESR.

At the beginning of beam operation, a 107Ag45+, was decelerated and delivered to HITRAP for continuation of HITRAP commissioning. As the 107Ag45+ was delivered from SIS18, no additional Stripper in the TE line had to be used, and a 50 MeV beam was decelerated in one step to the required 4 MeV/u and extracted, setup was fast, and the beam was available for HITRAP ahead of schedule.

This was followed by a short 5-day 78Kr32+.Laser spectroscopy experiment internal to the ESR. Here the ring was used in simple storage ring mode; the ion beam delivered from SIS18 was injected and stored at 286.6 MeV/u, electron cooled, bunched and handed over to the experiment in time.

Beginning of March 2025, a 3-week block with deceleration of 197Au79+ was used for the first physics experiment at HITRAP and later on for experiments at CRYRING@ESR. To reach the high charge states, an additional stripping of the 197Au65+ delivered from SIS18 was required. Best stripping efficiencies are around 400 MeV/u, therefore the deceleration in the ESR to 4 MeV/u had to be done in two steps with intermediate electron cooling to provide good beam quality at low energy. During this experimental block, repetitive extraction of both coasting and bunched beam to HITRAP was demonstrated for the first time. In case of coasting beam, the pulse length of the extraction kick was shortened to achieve two consecutive extractions. For bunched beam, bunching on the second harmonic and adjustment of the kicker timing allowed consecutive extraction of the two bunches.

Before the easter break ESR was set to isochronous optics mode for a measurement of mass and half-life of isotopes in the 116Hf region. A 208Pb67+was delivered from SIS18 and used for the setup of the ESR. After preparation of the ring with the primary beam, a production target in the transfer line from SIS18 to ESR was inserted to produce the desired isotopes, SIS18 extraction energy, ESR energy and charge are scaled to the appropriate values required for the specific isotope of interest.

The following experiment was aiming at laser spectroscopy of 208Bi80+.The settings of ESR were prepared with a 400 MeV/u 209Bi68+ from SIS18, stripped to 209Bi81+ in front of the ESR. The beam was cooled with stochastic cooling, accumulated, and decelerated to experiment energy. After execution of this complicated setup, a production target in the transfer line was used to produce a 208Bi81+ for ESR, which by charge exchange in the ESR electron cooler provided the 208Bi80+ beam for the experiment.

In the Uranium block an experiment on 229Th89+ was scheduled. This is similarly complicated setup as the one described for the Bi experiment above. This experiment was suffering from many failures of equipment along the whole accelerator chain that occurred because of high temperatures in this period and could not be concluded successfully.

The deceleration of a 400 MeV/u 238U91+ to 10 MeV/u and its extraction for an experiment in CRYRING@ESR concluded the 2025 operation period.

In addition to the physics experiments described above, during the times without scheduled experiments in ESR, machine experiments were carried out. Ion species that were available from SIS18 were transferred to ESR in parallel operation to physics experiments at other target stations without interference. Even during FAIR type test operation of booster mode in SIS18, delivery of beam to the ESR had no negative effect on the testing. This is a very promising development for execution of machine studies in ESR, as during scheduled ESR experiment operation only little time for these investigations is available.

Some of the results of these studies can be found elsewhere in this report, i.e., S. Litvinov et al.: "First Co-Circulation of Heavy Ion Beams in the ESR", A. Heintz et al.: "Beam-Based Optimization of the ESR Linear Optics Model", A. Sherjan et al.: "Machine Studies at the ESR". The co-circulating beams is certainly the highlight of the 2025 machine studies, potentially leading to a new type of experiment using low energy collisions of different ion beams, details can be found in the quoted report.

Another topic studied in 2025 is the beam accumulation (stacking) with barrier bucket or harmonic one bunching, in combination with electron cooling or stochastic cooling. The method is foreseen to be used for antiproton accumulation in the HESR in a future stage of the FAIR project, and we aimed at an experimental test of the procedure. The method makes use of injection of beam in presence of bunching, but the injected beam will longitudinally be located in the unstable region of the bucket, thus is not directly bunched. By applying beam cooling, this beam is moved into the stable region of the bucket and by this is captured. This is followed by the next injection and beam is accumulated in the bucket. The bucket can be a barrier bucket, which has the advantage of a large unstable area providing enough room for repeated injections, but it was also tested with regular bunching with harmonic one signal on the regular ferrite cavity used for acceleration/deceleration in ESR. In general, good agreement between simulation results and experiment were found. It is predicted that best accumulation is found for a moving barrier bucket and stochastic palmer cooling. For unidentified technical reason during the experiment the palmer cooling couldn't be used, and we applied other stochastic cooling methods (TOF, notch filter), and electron cooling. As expected here electron cooling leads to the best result (see Figure 106). The proof that palmer cooling and moving barrier bucket will lead to the most efficient stacking remains to be experimentally verified in the future.

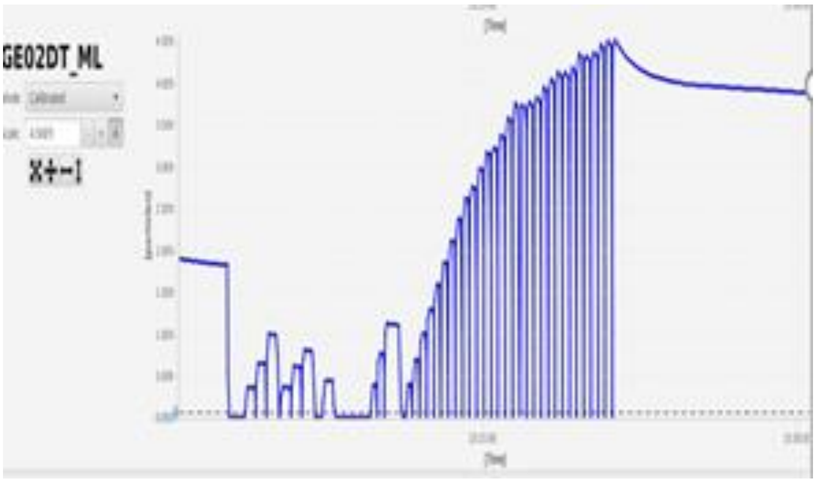

Figure 106: ESR Intensity vs time for stacking with H=1 and e-cooling, the saturation visible is predicted to set on significantly later with Palmer cooling.

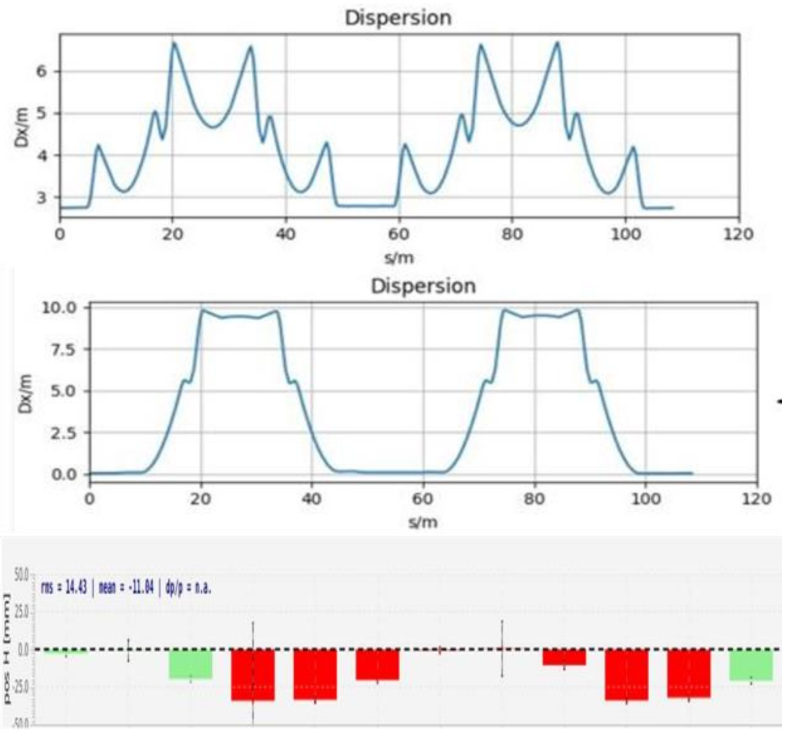

Figure 107: Model Dispersion Dx for standard (top) and new standard optics (middle), at the bottom the measured difference orbit for changed beam momentum and new optics (proportional to minus Dx)

It was also verified that an ESR optics setting with dispersion free straight section can be easily accomplished. The standard optics setting leads to non-zero dispersion in the straight sections. Model calculations showed, that a small adjustment of one of the 5 quadrupole families in the ring will lead to dispersion free straight section. The experimental test could proof that this has no negative impact on the ESR performance, injected and decelerated intensities remain practically unchanged. Figure 107 shows the modelled dispersion around the ring in comparison to a dispersion measurement using difference orbits when changing the momentum of the beam. In the future this setting will be used as new standard optics for ESR operation, as the zero dispersion removes the momentum dependence of orbit both at the electron cooler as well as at the target. Also, laser cooling or laser spectroscopy experiments, that require a good alignment of ion and laser beams, will benefit from this setting.

The test of a new ring orbit correction scheme for the compensation of the toroid magnetic field in the electron cooler was executed. The new scheme makes use of only two horizontal correctors in front and behind the electron cooler instead of previously four, while maintaining the injection performance. This scheme has the advantage of a more local correction, and a reduced corrector strength is required.

UNILAC Operation and Shutdown

Head: Uwe Scheeler (GSI)

Authors: H. Vormann, U. Scheeler, M. Vossberg

In 2025 the UNILAC was in operation for 127 days of user beamtime, six days have been used for operator training, 26 days for machine studies and dry run periods. The dry runs were used for tests of the new UNILAC control system, including tests with beam. With 16 days of commissioning (incl. RF conditioning) before the start of the user beamtime and 13 days before the uranium beam period (from the end of April on), the total operation time sums up to 198 days.

The beamtime started on 5th of February 2025 with a three weeks block of ^{107}Ag from the VARIS (Vacuum Arc Ion Source) High Current Source and ^{48}Ca from the ECR (Electron Cyclotron Resonance Ion Source) in parallel from 11th February on. In this calcium block it was tested and proven, that a sufficient beam intensity could be achieved despite the partly defect HLI-IH in-tank quadrupole triplet UN5QT4. From the VARIS ^{78}Kr followed for one week, in parallel with the Calcium beam. After that ^{197}Au was delivered for three and a half weeks in March from the VARIS and additionally from the PIG (Penning Ion Gun) (25 Hz long pulse operation for the materials research). After a two weeks block of ^{208}Pb (VARIS) and a maintenance and service period until Easter (21st April), another week of ^{197}Au beam was delivered. In May nine days of "mixed beam" (formerly "dual beam") were performed, with successful parallel operation of ^{12}C and ^{4}He (both ions in the same pulse) at the ECR, the UNILAC, the SIS18 and the HTM experimental cave. A one-and-a-half-week block of ^{209}Bi (VARIS) and ^{56}Fe (PIG) started with a short two days machine test with mixed ^{56}Fe and ^{209}Bi beam. Calcium was then delivered again from 16th May on, now for seven weeks, split into two blocks, with a two days ECR oven exchange service in between. Parallel to the Calcium beam two weeks of ^{12}C from methane (CH4) and one week of ^{40}Ar (MUCIS, Multi Cusp Ion Source) were performed, followed by uranium from the VARIS until the end of the regular beam time. Uranium was also used for machine experiments, partly with hydrogen stripping gas, including multi-charge beam tests ($^{238}U^{27+,28+,29+}$). The beam time 2025 finished on 14th July 2025. It was followed directly by a three weeks "Wet Run" for the development of the new linac control system.

The beam time 2025 was conducted with the HLI in-tank quadrupole triplet UN5QT4 in doublet mode (quadrupole UN5QT41 out of operation, due to defect), as already in the year before. The steerer magnets at the exit of the HSI-RFQ were still out of operation, due to a water leakage. Before the beam time the leaking RF coupler loop of the HLI-RFQ had been replaced. The Alvarez drift tube AIIDR105, suspected to be leak, was checked again, turned out to be okay (while a spare part had already been provided) and was therefore back in operation. The pulsed gas stripper and the new explosion safe roots pump stand were used during the full beam time. Unfortunately, related with a few technical restrictions: The pulsed stripping gas valves had shorter stand times than expected and were therefore used in a reduced variability mode. The roots pump had issues concerning oil consumption resp. oil circulation, requiring some few beam interruptions for maintenance.

The quadrupole doublet magnet UT2QD11 (Figure 108) showed field non-symmetries during the beam time (and strange ramping behaviour). The effect seems to be related to one coil having a winding short circuit. A spare has been ordered at an external producer.

Figure 108: The quadrupole doublet magnet UT1QD11 (UNILAC tunnel the end), to be replaced.

Commissioning of the CW advanced Demonstrator was performed with argon beam from the ECR (four weeks in March/April and one week in July).

In the shutdown 2025 the general modernization of the UNILAC experimental hall started, with the aim to provide up-to-date fire protection conditions. Most of the supply media for the UNILAC beam lines there had to be removed. The access control system (TVS - *Tür-Verriegelungs-System*) modernization is progressing, with the goal of completing it later in 2026.The Alvarez tank AII underwent a vacuum service, in particular the integrated buncher BB5 was dismantled, most of the large metal ring seals have been replaced. The defect drift tube AIIDR31 and the defect triplet UN5QT4 have not been replaced, as the spare parts were not yet available. Besides that, further smaller repair and maintenance work has been done.

Operation Infrastructure Support

Head: Dr. Gertrud Walter (GSI)

Authors: G. Walter, T. Dettinger, M. Henke, J. Holluba, M. Romig, S. Teich

Galvanic Workshop Activities for Alvarez 2.0

In 2025 the series copper plating of the tanks for the Alvarez 2.0 project has started and until end of 2025 five tanks of the entire series of 25 tanks have been plated. Meanwhile the plating process in the refurbished Galvanic is now well-established and the team is trained. Therefore, the series of Alvarez tanks including the cover flanges will be copper plated during the upcoming years. Some more details can be found in the Scientific report of 2024.

Technology Laboratory Activities for Campus Support

In 2025 the Technology Laboratory was ongoing to support a manifold of campus activities for running beam time as well as for the preparation of the FAIR commissioning by means of different R&D measures and supporting work, e.g., R&D for a new detector using thin Ti-foils, 3D precision measurements of chambers for the First Beam Event, R&D for standardised production of Cu seals, etc.

The main activity in 2025 was to prepare and install the high-vacuum soldering oven after dismantling the old one and after some necessary infrastructure measures. The new oven has been delivered at the end of2025, and the commissioning has been prepared to take place at the beginning of2026. In Figure 109a a photo of the inner part of the new soldering oven is shown.

Activities of Mechanical Workshop and Metal Working for Campus Support

The Department Mechanical Workshop and Metal working still supported the whole Campus in manifold activities. Some highlights can be pointed out.:

The welding procedures of SIS100 dipoles in the FAIR tunnel have been ongoing successfully during 2025. For the Alvarez 2.0 project some alignment works have been done. The post-processing of 3D printed miniaturised accelerator structures has also been continued in 2025, see Figure 109b-c. The new machines (CNC-based lathe machine with integrated milling units and a CNC-based plasma cutting machine) purchased in 2025 have been commissioned and are now in full operation. In addition, beam pipes have been produced for the connection between the GSI and FAIR high energy beam transport lines to support the planned First Beam Event.

Figure 109: a) Inner part of the high-vacuum soldering oven, b-c) miniaturised accelerator structure during and after post-processing, d) beam pipe for connection between GSI and FAIR high energy beam transport.

Machine Studies Statistics

Head: Dr. Stephan Reimann (GSI & FAIR)

Author: K. Grigoryev

At the beginning of 2025, the call for machine studies at the GSI accelerator complex was opened. In two months, 53 internal proposals were collected. From February on, the beamtime last almost six months with only minor interruptions. A dedicated window for machine development studies was foreseen for only eight days. The largest test block was planned for the end of beamtime from July 7 to 13 (KW28). Assuming every test required a single 8-hour operating shift, including preparation and optimization of the beamlines for experiment needs, only about half of the requested experiments could be conducted.

All proposals were discussed at the machine coordination meeting, where priorities were set and 45 were planned to be conducted during the year, with the possibility of some running in parallel to main experiments without affecting them. This worked very well for CryRing, which has its own injector and can operate independently from UNILAC. Parallel machine studies at the ESR storage ring were organised differently: if the injection chain from SIS18 was already prepared, ESR could request new injection every minute without affecting the duty cycle of other experiments.

During this period, many studies used the "Standard Beam" preparation scheme, using a single beam species and charge at a time. Nevertheless, some experiments used special technical challenges during their beam preparation. For example, at the end of May, experimentalists were using the "Molecular Ion Beam" from the HSI source with methane (CH4) simultaneously delivered Carbon ions and Protons after the Gas Stripper. On May 9, the "Dual Sequential Beam" operation combined Fe and Bi, produced by two different HLI sources, injected sequentially into SIS18, with acceleration after the second beam's injection. A similar sequential operation with Uranium beams into SIS18 occurred at the end of the main experiments block on July 11. The "Multicharge Beam" scheme was used during the experimental week on July 9 to achieve higher currents of injected beam by simultaneously injecting two or three different Uranium charges into SIS18. The "Dual Parallel Beam", where two different ions from two different HLI sources are simultaneously injected into the UNILAC, was not part of the studies.

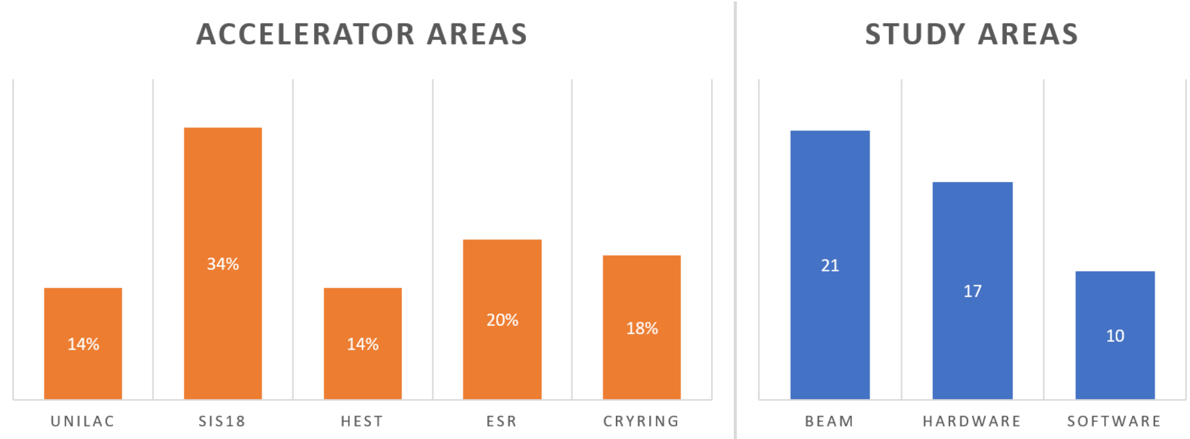

Figure 110: The left diagram shows machine study areas distribution across accelerator zones, while the right diagram shows the regions of interest.

Advance information from experimentalists significantly impacted and simplified planning and operations, permitting the operating crew to stay flexible and prepare the beamlines in advance. The field of interest was evenly distributed across machines, except SIS18, which attracted roughly twice as many experiments. Likely it is reflecting preparation for SIS100 and other new facilities. Groups were roughly 40% focused on hardware, 40% on beam, and about 20% on software and Machine Intelligence studies (see Figure 110). After completing all studies, each group presented results at a dedicated meeting by the end of the year (the talks are available online at https://indico.gsi.de/event/23427/).

11.3 Accelerator upgrade projects

Progress report on the post-stripper upgrade (PSU) - Alvarez 2.0

Head: Dr. Lars Groening (GSI)

Author: S. Mickat

The existing post-stripper drift tube linac (DTL) of the UNILAC has been in operation for more than 45 years. In 2012, a dedicated report on its state and perspectives drew attention to increased failure rates and downtimes from significant aging. Additionally, its design from the 1960s does not foresee intense beams of heavy ions as being mandatory for FAIR. The "Alvarez 2.0" project started in 2017 with a dedicated first-of-series (FoS) cavity section, which was tested successfully in 2021. Since

2022, the procurement of series components has been ongoing (see S. Mickat et al., "Series procurements for the new post-stripper DTL Alvarez 2.0" in [1]).

In 2025, the remaining 10 cavity sections with four end plates assigned to the cavities AIII and AIV were delivered (see Figure 111). The order of a total of 25 cavity sections with ten end plates was therefore completed, and the five tank sections of cavity AIIa were successfully copper-plated by the team of the GSI galvanic workshop. Regarding the drift tubes, the study for the longest drift tube in cavity AIV was completed with an unsatisfactory result, as the magnet design did not meet the pulsed operation requirements. The contractor has substituted its sub-supplier of the magnet system with another supplier, who has already demonstrated that his design copes with the mechanical stress in pulsed operation. This new sub-supplier was awarded as the main-supplier of the contract for the AIIb, AIII, and AIV drift tubes and is the main-contractor of the AIIa drift tubes, which have already produced in series and subsequently Cu-plated at CERN's galvanic workshop. Currently, 25 drift tubes of cavity AIIa were plated and shipped to GSI for pre-assembly and testing. The adequate and mandatory areas in the GSI testing hall (TES) were provided in the second half of 2025 (see Figure 112 and Figure 113). Furthermore, different activities were in progress concerning the procurement of add-on parts and developing solutions to simplify and optimize the alignment of the drift tubes and the media supply installation.

Until 2025, almost 16.3 M€ had been spent and committed for series components. The GSI Supervisory Board has approved the application for a release of further 9.3 M€ until 2030 out of a total of 35 M€ for project implementation and the procurement of additional series components such as magnetic power supplies or RF amplifiers. Thus, the Supervisory Board supports the release application to the BMFTR (Federal Ministry of Education, Research, Technology and Space).

Highlights

Figure 111: External storage area in Pfungstadt for the large-scale components – cavity sections and end plates.

Figure 112: View into cavity section AIIa-1 with hanging drift tubes at the GSI Testing Hall (TES).

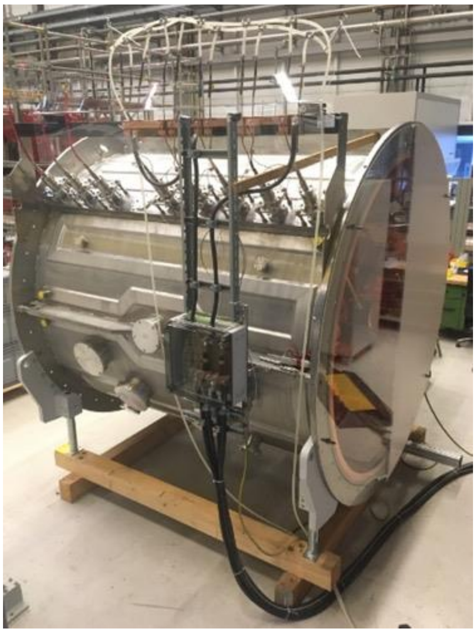

Figure 113: Cavity section AIIa-1 equipped with the electrical supply system to be tested at the GSI Testing Hall (TES).

Outlook for 2026

In 2026, the Cu-plating of the cavity sections at the GSI galvanic workshop shall continue. The focus will be on the activities in the workshop and on the optimization of the process with the existing resources and infrastructure. Also, the pre-assembly of cavity AIIa shall be pushed to start LLRF (Low Level Radio Frequency) tuning of the cavity. Concerning the drift tubes, the completion of series production for cavity AIIa is foreseeable. Afterwards, the production of drift tubes of cavity AIIb and cavity AIII and their subsequent Cu-plating at CERN shall follow. A chain of five hanging AIIa drift tubes shall be operated in pulsed mode to analyse mechanical vibrations caused by re-pulsing forces of conductors of the magnet windings. After this test run, sub-components of the electrical supply system shall be tendered and procured, including the power supplies. An ongoing task will be the planning of the replacement of the existing Alvarez Drift Tube Linac (DTL) with the Alvarez 2.0 DTL in the 2030s. A 3D model of the DTL in the UNILAC tunnel is detailed step by step to plan the necessary shutdown activities for substitution

Pulsed gas-stripper: beam time operation and project status

Head: Dr. Lars Groening (GSI)

Author: M. Maier

In 2025, the pulsed gas stripper project [2] progressed significantly toward routine operation. Using the stripper during the full beam time enabled the implementation and successful validation of several essential system upgrades.

Beam-time 2025 commenced in February with user beam times including dry and wet runs dedicated to the upgrade of the control system and concluded in July. During this period, stripping data were acquired for various ion species. Measurements were performed using two different valve exit orifices. Operation with a reduced orifice size allows to rise the pressure running the valves closer to their specified pressure limits of a few bars and is therefore expected to prolong the valve lifetime. At the same time this orifice reduction simplifies pressure control and no degradation of stripping efficiency was observed as shown in Figure 114. Electronic pressure controllers were deployed and qualified for pressure regulation. Their qualification represents a key prerequisite for the automated gas control station required for routine operation. Based on these results, the tender for the gas control station was finalised, and a supplier was selected. Delivery is scheduled ahead of the user beam time in 2026. In parallel, the next-generation x-stripper, featuring four independent valves compared to the two-valve configuration of the current v-stripper, entered production. Commissioning of the x-stripper is planned for summer 2026.

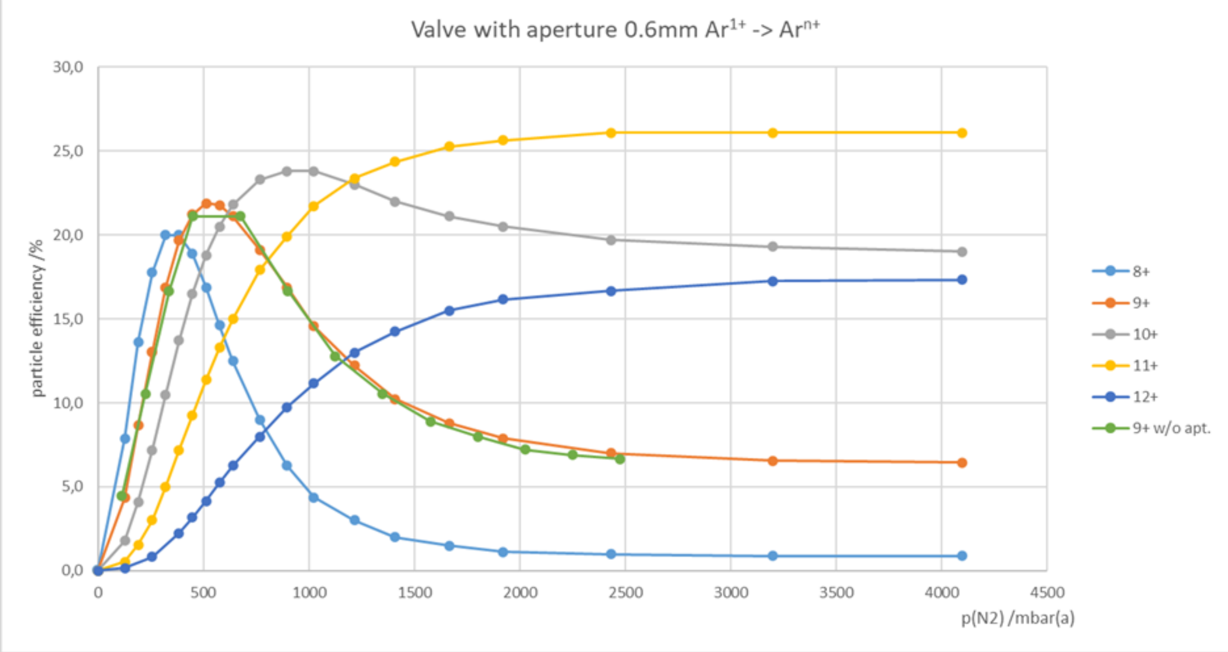

Figure 114: Stripping efficiency for the charge states 8+ to 12+ of ^{40}Ar as a function of the applied gas pressure with the new valve with an outlet orifice of 0.6 mm and for comparison 9+ in green without orifice and the pressure scaled by a factor of 4.5.

A major milestone in 2025 was the replacement of the defective roots pump, which had caused persistent oil leakage and significant operational effort. Pfeiffer replaced the OKTA 8000 pump with two OKTA 5400 pumps equipped with magnetic seals. Due to the extremely limited space available in the UNILAC basement, the installation was technically demanding and was successfully completed with the support of external experts.

Furthermore, simulations of a hydrogen dilution device located downstream of the explosion-proof pumps and upstream of the vacuum exhaust were completed. The results led to a conceptual design that is currently under evaluation with potential manufacturers. The system is expected to reach routine operation with nitrogen in 2026. Installation of the gas control station and its integration into the GSI control system are scheduled for completion before beam time starting in August 2026. The dilution device and the interlock system, both required for regular hydrogen operation, are planned for installation during the shutdown in 2027. Upon completion, all prerequisites for routine hydrogen operation will be fulfilled, allowing formal system acceptance.

Status of the UNILAC control system upgrade

Head: Dr. Lars Groening (GSI)

Author: *P. Gerhard and H. Hüther*

The UNILAC control system upgrade started end of 2019 as the first and major part of a broader Injector Controls Upgrade (ICU) project [3]. It aims at developing a new control system for the linear injector accelerators and ion sources of the GSI/FAIR facility, based on the LSA framework and White Rabbit timing. The user beamtime 2025 was the final operation period of the legacy control system. Together with the decommissioning of the UNILAC "Pulszentrale", this constituted a major milestone of the project. Additionally, moving the Main Control Room (MCR) to the new Fair Control Centre (FCC) building requires replacing many analogue and hardware-based systems and equipment located in today's MCR, which will not be relocated.

The transition strategy adopted in 2023 set the user beamtime 2025 to be the last time operating the more than 30 years old legacy control system and the UNILAC Pulszentrale (the central, integrated timing, interlock and chopper control system). As a backup solution, an intermediate, minimum viable version of the new control system has been provided by the end of 2024. However, as anticipated, the beamtime was successfully operated with the legacy system, and the backup was not needed.

In parallel to the beamtime, the initial production version of the new LSA-based control system has been developed. Using the intermediate version as the basis, simplifications made therein were replaced by fully fledged solutions, and missing features retrofitted. A core part of this development was a thorough revision of the control system's operating concept of Chains and Patterns. While both Chains (representing physics and hardware settings for a specific beam in a specific part of the facility, e. g. UNILAC or SIS18) and Patterns (describing the order in which multiple Chains are executed) still remain the central settings management concepts, they have been refined using insights gained from past beam times and extended to meet new requirements. The concept of so-called Stand-alone Chains, which allows for Chains to be placed more flexibly within a Pattern, was invented to operate the UNILAC, but it also allows for a unified and enhanced operation of all accelerators at GSI and FAIR. This refined Pattern concept, which is now being implemented, resembles much of the original ideas of what Patterns were intended to be. Other parts of the control system, especially the applications, had to be upgraded and adapted accordingly. These very fundamental changes of the control system architecture intentionally entailed some changes in the basic processes and behaviour of the control system, which will contribute to the more complex operation of FAIR. One of the main points is that beam is transferred from one accelerator to another not on request anymore, but via pre-calculated, fixed schedules, which eliminates response times and enhances efficiency throughout the facility.

The second test run for the new UNILAC control system with beam (also called a "wet run") was scheduled for July, immediately after the user beam time. This was also the first test with UNILAC and SIS18 together with beam and the first test of the initial production system. For three weeks, UNILAC and later SIS18 were solely operated via the new control and timing system. Within one week, UNILAC was brought to full performance, delivering beams from all three sources to 6 destinations. The first beam injection into SIS18 was achieved at the beginning of the second week, after only two days of preparation. Finally, all standard and advanced injection schemes including Multi-Multiturn and Dual Beam could be demonstrated successfully. As expected, a reasonable number of bugs were found and fixed during the wet run in order to achieve these results. Operational efficiency of UNILAC with the new control system was found to be greatly increased with respect to the last wet run, demonstrating readiness of the core system for the beamtime 2026. The same holds true for SIS18, although interaction between both accelerators still has to be improved. Despite these achievements, it remains clear that, in order to again reach the levels of flexibility in beamtime planning required by the stakeholders, considerable effort needs to be put in extending and fine-tuning the system.

Workarounds, changes and bugfixes implemented before and during the wet run were cleaned up in the aftermath. For the rest of the year, the main focus of development shifted towards extending the unified pattern concept to the other accelerators left out so far as well as implementing features required for the beamtime 2026. For UNILAC, since core functionality has been accomplished, developers could attend to more specific topics, essential details and enhancements of preliminary solutions.

The next and final wet run before the new control system will be operated for its first user beamtime is scheduled for January and February 2026. In preparation of both the test run and the beamtime, an introduction was provided to the operating staff during the operator school in November. In total, five lectures on the new control system were held. Hands-on training will be an integral part of the test run, with another full day of lectures beforehand. Since development of the operating applications in particular will continue right up to the beamtime, another more comprehensive operator school is planned for spring next year.

Recent Upgrades and Modifications of the GSI-HEBT

Head: Dr. Stephan Reimann (GSI)

Authors: C. Hessler, U. Clausen, O. Geithner, S. Strohmenger, Y. Valdau, and B. Walasek-Höhne

The High-Energy Beam Transfer lines at GSI (GSI-HEBT) transport the beam to the experimental stations downstream SIS18 and to the storage rings ESR and CRYRING@ESR. Furthermore, the new beamline to FAIR "T1S1", which is part of the High-Energy Beam Transfer of FAIR (FAIR-HEBT), will branch off from the first section of the GSI-HEBT beamline "TE", which links SIS18 with the ESR and the SIS experiments. The installation of the FAIR HEBT has been started in 2025, and the first test beam towards FAIR was planned for December 2026 at the time of writing this article. To make GSI-HEBT ready for FAIR, several upgrade measures and modifications are ongoing or have been started in 2025, which will be discussed in this article.

Upgrade of luminescent screen stations

An upgrade program to replace all analogue cameras of the luminescent screen stations with digital cameras is on-going since 2023 (see C. Hessler et al., "HEST-Upgrades" in [4] and C. Hessler et al., "HEST-Upgrades" in [1]). This update is required because the new control room in the FAIR Control Centre (FCC), which will be put into service in 2026, will be fully digital without analogue cable links. Furthermore, analogue cameras are disappearing from the market, and the spare situation is becoming more and more difficult. The new cameras are integrated into the CUPID system (Control Unit for Profile and Image Data), and the mechanics (pneumatic drives) are adapted to the new hardware. The corresponding diagnostic vacuum chambers are modified to equip them with fiducials for precise adjustment of the screen position.

During the shutdown 2025/26, the upgrade of the remaining six analogue cameras has started and will be completed by the end of this shutdown in 2026. This includes all cameras in the beamline towards cave M, one camera at the central bifurcation area of the beamlines to the target hall, and one camera in front of the HHD beam dump. The upgrade of the latter two cameras is challenging due to the tight space constraints and interferences with other shutdown work (exchange of the concrete shielding bars above the SIS18 extraction area).

Refurbishment of power converters

The power converters of GSI-HEBT date back to 1990, and due to their age, failures and issues are increasing. Therefore, it is planned to refurbish or exchange all power converters of GSI-HEBT over a period of 10 years within the scope of the GSI accelerator roadmap. As a first step, the power converters of the three magnets in the TE line, which will also be used by the FAIR beam, will be refurbished to increase their reliability for FAIR operation and to upgrade them to FAIR standard. During this upgrade, the power converters receive new power components and new control units. In 2025 the refurbishing of two quadrupole power converters has started, and a steerer power converter will follow in 2026.

Modification of TE beamline for FAIR connection

The installation of the first section of the beamline towards FAIR was originally planned for 2025. The new beamline branches off the same dipole magnet GTS1MU1 as the beamline serving the fragment separator (FRS). Consequently, the area will be extremely densely populated with beamline equipment after installation of the T1S1 line. The first quadrupole and the first main dipole magnet in the FAIR beamline will be located very close to the existing beamline. The first quadrupole was already designed with a cut-out in the iron yoke to avoid a collision with the beam tube of the TE line.

However, several more collisions of components of the new beamline with equipment of the existing TE line have been discovered in the 3D model shortly before the start of the installation work: There were interferences of the first main dipole magnet in the T1S1 line with a beam position monitor (BPM), an ion getter pump and bake-out jackets of the TE line. Furthermore, supports of the new beamline were interfering with the connection boxes for the bake-out equipment and with other supports of the existing beamlines (Figure 115).

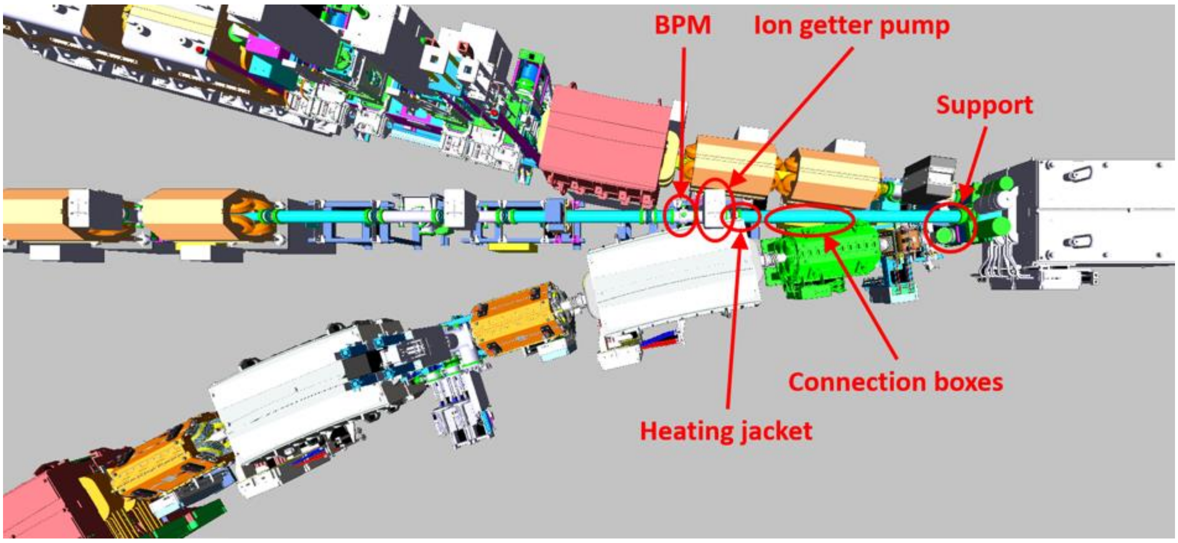

Figure 115: Old (planned) layout of the branching point of the FAIR beamline with the different collisions indicated with red circles. The TE line is the beamline in the centre, the upper beamline serves the fragment separator, and the lower beamline FAIR (T1S1 line).

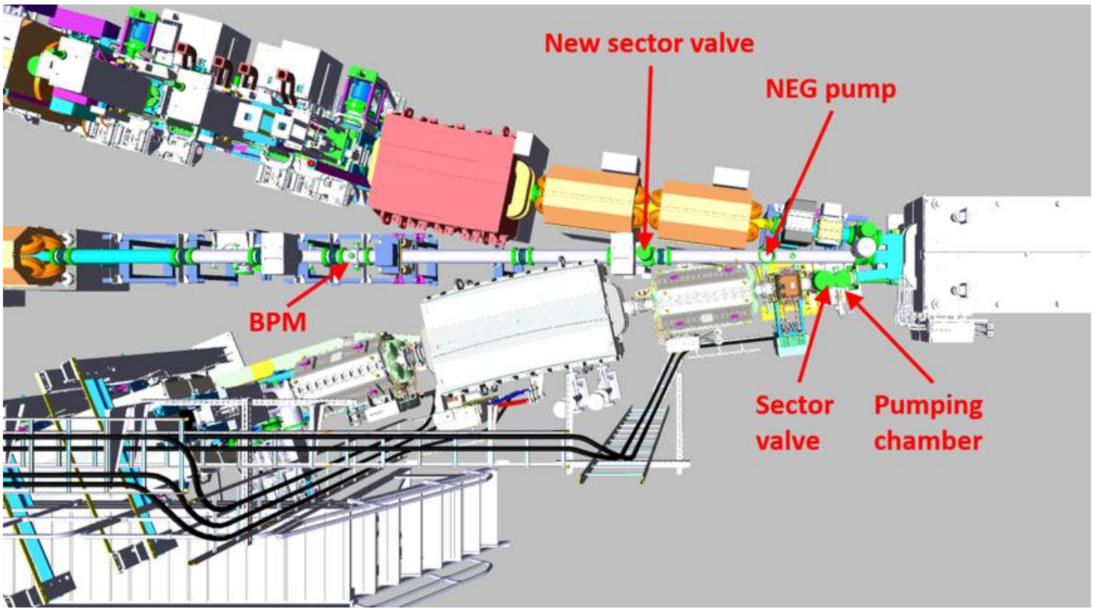

Figure 116: New layout of the TE line at the branching point with the shortened baked vacuum sector ending at the new sector valve. The figure shows the beamline to the fragment separator (upper beamline), the TE line (beamline in the centre), and the T1S1 line to FAIR (lower beamline).

To solve these issues, the BPM and the pumping chamber with the ion getter pump had to be relocated. To avoid the collision of the dipole magnet with the heating jacket, a clamp of the magnet had to be redesigned and rebuilt. Furthermore, the baked sector of the TE line has been shortened by splitting it into two sectors: a baked and an unbaked one. This should not have any negative impact on the SIS18 vacuum, since the vacuum sectors of the FRS and FAIR beamlines starting directly downstream of

GTS1MU1 are unbaked anyway. Nonetheless, a NEG pump will be added to the shortened baked sector as an additional safety measure. A consequence of the shortening of the baked vacuum sector is that the vacuum chamber, which was originally used for initial pumping down of the beamline, is not part of this sector anymore. Therefore, the first vacuum chamber in the T1S1 line located directly downstream of the sector valve will be swapped with the sector valve and will be used for initial pump down of the baked sector of the TE line in the future. This redesign of the vacuum system required the construction of new vacuum pipes and supports, as well as the procurement of heating jackets and the installation of an additional vacuum gauge.

To avoid the collisions of the supports of the T1S1 line with the connection boxes of the bake-out equipment and supports of the existing beamlines, the electric part of the bake-out system of the TE line is being rebuilt at a new position using new FAIR-type connection boxes. The cabling of the existing heating jackets has to be adapted accordingly. Furthermore, the first support in the T1S1 line had to be modified. The new layout of the area is shown in Figure 116. The work at the TE line started in October 2025 and is expected to be completed in the second quarter of 2026.

Status of FAIR Commissioning

Head: Dr. Stephan Reimann (GSI & FAIR)

Authors: S. Reimann, V. Kamerdzhiev

During the reporting period, the focus of the FAIR Subproject Commissioning shifted from predominantly planning and developing commissioning workflows to initiating the first major commissioning activities and to project steering. In particular, commissioning of the Cryo2 cryogenic plant progressed from preparation to execution. In parallel, the commissioning governance (Gate Reviews) and the associated documentation templates were prepared and applied for the first time at Cryo2 as a pilot; the experience gained is being used to refine the approach and to support the upcoming hardware commissioning, including the High Energy Transfer Lines (HEBT) subproject, where hardware commissioning is scheduled to start in April 2026.

Planning status and key milestones

In 2025, the FAIR Subproject Commissioning further consolidated its planning framework towards First Science. The integrated commissioning plan covers the full path up to First Science and is linked to the wider campus planning via the Integrated Campus Schedule, ensuring conflict-free alignment of key activities across the FAIR/GSI campus.

The main milestones and achievements for 2025 were:

- establishment of the commissioning and safety organization for Cryo2,
- development of a structured handover process from installation to commissioning,
- start of Cryo2 commissioning,
- finalizing the specifications, procurement and installation of consoles in the new main control room at FCC,
- start of the procurement process for the MCR overview display system.

Cryo2: gate review and commissioning start

To ensure a safe and orderly transition from installation to commissioning, the Gate Review process (readiness criteria, responsibilities, and checklists) was developed in 2025 and prepared for the first practical application.

A major step in 2025 was the successful execution of the Cryo2 commissioning Gate Review for the building K0720A. As the final element of this Gate Review, a dedicated safety inspection was conducted. Following this, the commissioning-phase safety organization was put into force and key responsibilities of the facility within K0720A were handed over to the commissioning team (Figure 117).

Figure 117: Handover of K0720A (Cryo Building and Compressor Building), 13 August 2025.

Subsequently, Cryo2 commissioning activities started: commissioning of the electrical power supplies was initiated, the first start of compressor motors was carried out, and preparatory work on the compressors and the refrigeration system began. The aim is to complete the Cryo2 commissioning by August 2026.

FAIR Control Centre (FCC): procurement and readiness for main control room commissioning

In 2025, FCC activities concentrated on preparing the commissioning of the new main control room, with commissioning start planned for February 2026. Key work packages covered specifications, procurement, and installation of the operator workplace infrastructure.

The console prototype was accepted at the manufacturer's site at the end of August. The production and delivery of the console furniture were progressing according to plan with 85% of installation completed in December (see Figure 118). The specification of the LED overview displays was released, and the procurement process initiated. In parallel, a first set of 24/7 control room chairs was delivered to GSI for operational evaluation and final specification. All necessary decisions were made, and the purchase orders for all types of chairs were placed in December.

The purchase order for the computers and monitors to be integrated into the consoles was placed in December, ensuring availability for integration and subsequent functional checkout during the commissioning phase.

Figure 118: Main Control Room of the FAIR Control Centre, equipped with consoles including integrated screens.

HEBT: commissioning and First Beam Event preparation

Preparation for the commissioning of the High Energy Transfer Lines (HEBT) and the First Beam Event (FBE) advanced significantly in 2025. A dedicated project description was prepared for key stakeholders and the relevant authorities. Baseline parameters for the pilot beam were defined, and a high-level schedule for 2026 was established. The hardware commissioning is planned to start in April 2026, beam commissioning blocks are foreseen for October/November 2026, and the FBE is targeted for December 2026.

To coordinate the FBE preparation activities, a bi-weekly task force meeting was established in April 2025 and continued throughout the year, providing a regular forum to track progress, address interfaces, and manage the critical path towards the first beam on the FAIR site.

Second FAIR Commissioning Workshop

The 2nd FAIR Commissioning Workshop took place on 27–28 November 2025 (Hotel Bessunger Forst) with 44 participants (see Figure 119), including contributors from DESY, ESS, and CERN. Early Science was the major focus of the workshop. In a dedicated session, experience in commissioning of cryo plants and distribution systems was discussed. Furthermore, gate reviews, handover processes, and safety organization, as well as commissioning plans for the First Beam Event and Early Science, were presented and discussed. In addition, parts of the First Science plans were presented.

Figure 119: Participants of the Second FAIR Commissioning Workshop.

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11.4 Accelerator R&D Activities

Machine Studies Statistics

Head: Dr. Ralph Hollinger (GSI)

Authors: R. Berezov, R. Hollinger

The Penning Ionization Gauge (PIG) ion source provided different ion species as $^{56}Fe^{2+}$ (9 days), $^{52}Cr^{2+}$ (14 days), $^{50}Ti^{2+}$ (20 days) and $^{197}Au^{8+}$ (26 days) for the user beam time 2024 with sufficient performance and in stable operation. The $^{56}Fe^{2+}$ for material research, HTA, ESA and biophysics program were performed with a low duty cycle 5 Hz at 1 ms during 9 days with life time of PIG source of 150 hours. $^{197}Au^{8+}$ was delivered for material research with a higher duty cycle 25 Hz at 3 ms during 26 days with estimated life time 40 hours and $^{50}Ti^{2+}$ was run for super heavy elements with maximum performance of ion source 50 Hz at 5 ms and a life time of 20-24 hours.

The delivery of $^{52}Cr^{2+}$ for NUSTAR groups (laser spectroscopy and super heavy elements) and for atomic and plasma physics application with a duty cycle of 50 Hz at 5 ms was the main highlight about PIG performance during this beam time 2024. Cr has 4 stable isotopes: ^{50}Cr (4.34 %), ^{52}Cr (83.8 %), ^{53}Cr (9.5%), ^{54}Cr (2.36 %), where the maximum percent ratio belongs to ^{52}Cr. In this case the ion beam production from this isotope has several advantages: we can use nature materials and we can achieve already high current value with low arc-current performance of ion source that lead respectively to the higher life time. By using nature materials all isotopes have to be separated in the low energy beam transport (LEBT) section before RFQ entrance. Figure 120 shows the separation of nearest isotopes, which has been measured at the profile grid (GUR5DG7) behind the bending magnet and confirms that ^{52}Cr can be easily separated from other isotopes by using slits in the LEBT.

A total operation time of 14 days during beam time has been obtained using seven sputter PIG-sources, which leads to a service life time of two days for each ion source. The life time and stability during the beam time were two times higher compared to the production of ^{50}Ti. The beam stability of $^{52}Cr^{2+}$ was quite high for all cathodes during the beam time. The operation stability and beam intensity during 100 minutes of operation is shown on Figure 121. An intensity of 0.12 emA has been achieved in front of the of the High Current Injector (HSI)-RFQ fulfilling the request of one particles microampere of $^{52}Cr^{14+}$ in the experimental area X8 (UX8DT3).

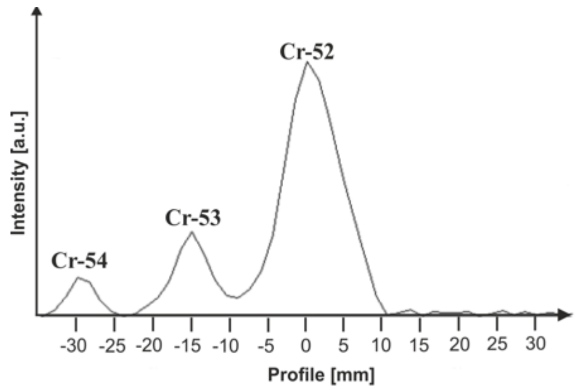

Figure 120: ^{52}Cr, ^{53}Cr and ^{54}Cr at profile grid GUR5DG7.

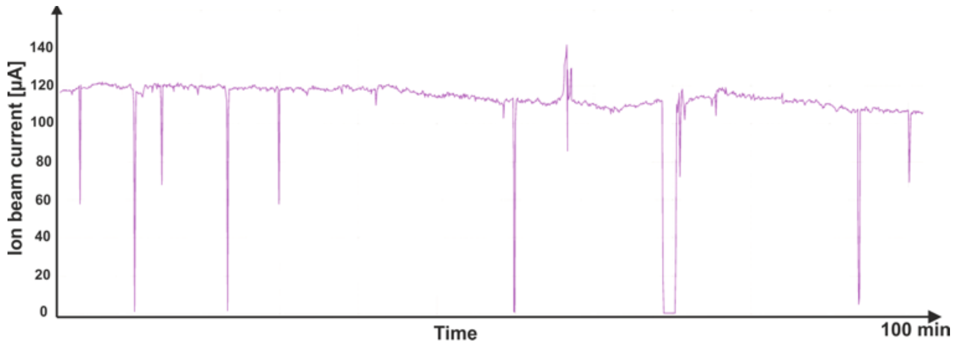

Figure 121: Operation stability and intensity of $^{52}Cr^{2+}$ over 100 min at beam transformator GUR5DT8.

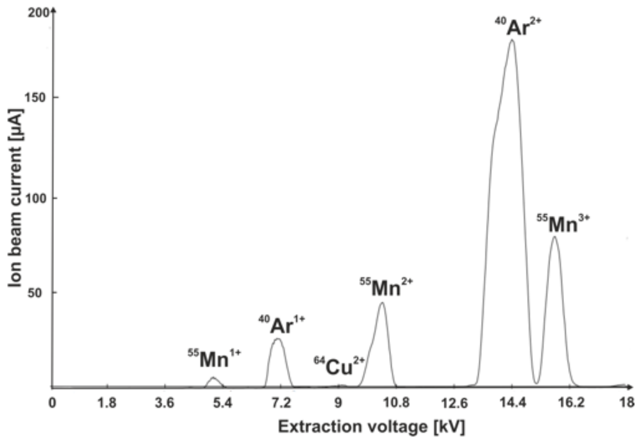

Figure 122: Manganese, argon and copper charge spectrum.

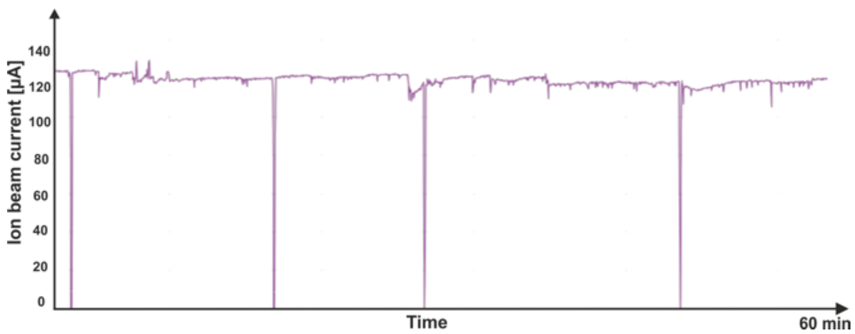

Figure 123: Operation stability and beam intensity of $^{55}Mn^{3+}$ over 60 min measured in section GUR5DT8.

Test with ^{55}Mn in Terminal South was performed in March 2024 for ongoing development for the future beam time. The manganese electrodes mixed with copper Mn-Cu (5%) were manufactured by HMW Hauner GmbH. Figure 122 shows charge spectrum including $Mn^{1+,2+,3+}$, Cu^{2+} and argon $Ar^{1+,2+}$ that used as auxiliary gas in PIG sources. $^{40}Ar^{2+}$ and $^{55}Mn^{3+}$ were separated in the LEBT before RFQ section. The first test with maximum duty cycle of PIG source 50 Hz and 5 ms has been carried out by measuring the beam intensity behind switching magnet directly in front of the quadrupole quartet. The Mn^{3+} current of 120-130 µA measured in section GUR5DT8 is depicted in Figure 123. The preliminary result shows very stable operation with small number of sparks and high duty cycle. Since a high intensity was achieved with small value of arc current the life time of approximately 2 days for each ion source similar to ^{52}Cr operation is expected. Further tests at the gas stripper section have to be done in order to more precisely define beam performance and intensity to the experiment area.

The authors would like to acknowledge the beam operating crew for their support during PIG ion source operation.

Recent Progress in Metal Additive Manufacturing R&D at GSI and for FAIR

Head: Dr. Chuan Zhang (GSI)

Authors*: Chuan Zhang, Roland Böhm, Eduard Boos, Ramy Cherif, Alexander Japs, Stefan Wunderlich*

As early adopters of Metal Additive Manufacturing (MAM) for particle accelerator and storage ring R&D, the RACERS (Research on Additive Construction for Efficient Resonating Structures) team—initiated by the GSI Stochastic Cooling (SCO) Group—is currently advancing three projects [1]: 1) RACE (Resonators Additively Constructed for Experiments) Project: the flagship effort focused on realizing a table-top 704.4 MHz CH (Cross-bar H-mode) cavity fabricated using MAM; 2) SHAPER (SH Additively Produced as an Efficient Resonator) Project: the development of an advanced 704.4 MHz SH (Sextupole H-mode) cavity based on MAM; 3) SCO Project: the design and fabrication of an efficient cooling plate for 1–2 GHz Collector Ring Stochastic Cooling (CRSC) kickers at the Facility for Antiproton and Ion Research (FAIR) [2], enabled by MAM. Operating at ultra-high frequencies (0.3–3 GHz), these RF structures exhibit football-sized transverse dimensions while imposing stringent requirements on compact and highly efficient internal cooling channels. MAM overcomes the limitations of conventional fabrication techniques in realizing complex geometries and intricate internal features, thereby offering a highly promising solution.

RACE Project

Figure 124: Left: the RACErs team with the assembled additively manufactured table-top RACE cavity prior to copper plating. Right: the 704.4 MHz RACE cavity after copper plating.

Early R&D efforts on the highest-frequency (704.4 MHz) and first additively manufactured RACE CH cavity were reported in [3][4][5][6]. In 2024, the RACE cavity was fully fabricated by MAM, with the electrodes printed in pure copper and the tank in stainless steel (see Figure 124). Low-level RF measurements conducted in February 2025 at IAP Frankfurt — and repeated in June 2025 at GSI — successfully reached the design frequency, with the measured gap-voltage distribution in good agreement with CST simulations. Copper plating of the cavity (except the copper electrodes), kindly supported by FZ Jülich, was completed in December 2025. Currently, vacuum tests and a second low-level RF measurement campaign are under preparation. For the planned high-power RF tests and subsequent beam experiments, a 704.4 MHz, 4 kW pulsed power amplifier has been developed, and a copper RF coupler, designed for realization via MAM in collaboration with IAP Frankfurt, is currently under preparation for fabrication.

SHAPER Project

In parallel, a 704.4 MHz SH cavity designed for accelerating 33 MeV protons is under development. As a new member of the H-mode Drift-Tube Linac (DTL) family, the SH structure operates in the $H_{31(0)}$ mode. Figure 125 presents the mechanical design of the 704.4 MHz SHAPER SH cavity together with one of the additively manufactured cavity segments. Unlike the RACE cavity, the SHAPER cavity adopts a piecewise fabrication strategy for several reasons: 1) Assembly feasibility: each SH electrode comprises three stems arranged 120° apart, rendering the insertable-electrode concept used for the RACE CH cavity impractical; 2) Surface accessibility: the additional stem significantly restricts access to internal surfaces if the tank was printed as a single piece, whereas segmented fabrication enables direct post-processing and copper plating of individual segments; 3) Cost and flexibility: the modular approach reduces fabrication costs by avoiding the need for a large build volume, thereby broadening the range of qualified suppliers. The SHAPER cavity segments were printed in stainless steel 316L and will be copper plated at a later stage. After two rounds of blasting, a surface roughness below Rz 8–10 µm was achieved. Vacuum tests of the newly developed sealing concept, employing standard CF seals with copper gaskets, are planned for Q1 2026. To the best of our knowledge, the SHAPER cavity represents the first sextupole H-mode DTL structure ever realised.

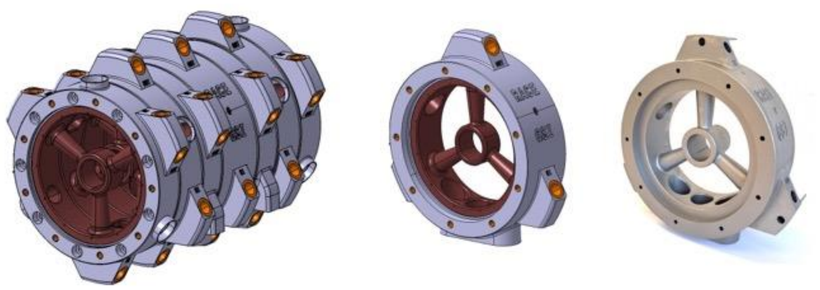

Figure 125: From left to right: mechanical design of the 704.4 MHz SHAPER cavity; drawing of a SHAPER cavity segment; a SHAPER cavity segment printed in stainless steel 316L.

SCO Project

The SCO project focuses on the R&D of a novel cooling plate for 1–2 GHz CRSC kickers at FAIR using MAM. This effort is intended to address the worst-case operating scenario in which the power dissipated in the resistors of a divider board reaches 95 W for a duration of 5 minutes, causing the resistor temperature to exceed the maximum permissible operating limit of 140 °C after approximately 100 s. As a first step, a test specimen (dimensions: 48.5 mm × 97.0 mm × 10.0 mm) incorporating an internal “SCO”-logo-shaped cooling channel was fabricated via multi-material MAM. CuCr1Zr — a copper alloy with slightly reduced thermal conductivity but enhanced mechanical hardness compared to pure copper — was used for the main body, while stainless steel 316L was employed for the inner cooling-channel wall with a thickness of 2 mm (see Figure 126). The surface finish quality achieved with this multi-material printing approach was inferior to that obtained with the single-material printing used for the RACE and SHAPER cavities. One possible explanation is that, although CuCr1Zr and stainless steel 316L have similar coefficients of thermal expansion, their thermal conductivities differ significantly — approximately 310 W/(m·K) for CuCr1Zr versus about 15 W/(m·K) for stainless steel 316L. This mismatch in thermal conductivity results in pronounced temperature gradients across the CuCr1Zr–stainless steel interface, thereby inducing remarkable thermal stresses.

For the real-scale cooling plate (dimensions: 123.0 mm × 198.5 mm × 15.5 mm), taking into account the actual resistor distribution, two versions have been fabricated entirely from CuCr1Zr using a single printing material: version A with a single-channel design and version B with a gyroid-structure design [7]. ANSYS simulations at a thermal load of 95 W indicate that, while only marginal differences are observed under steady-state conditions (with maximum temperatures below 75°C for both designs), the gyroid-structure cooling plate exhibits a pronounced advantage under transient thermal loads (5 min), significantly reducing the maximum temperature (@ 67.7°C compared to @ 80°C for the single-channel design). Detailed analyses, post-processing, and experimental testing of these components will follow.

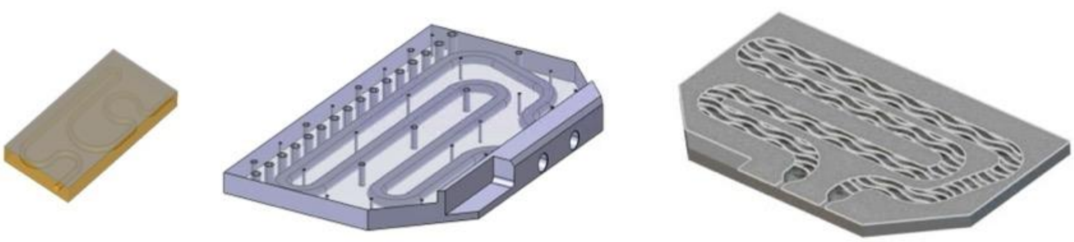

Figure 126: From left to right: multi-material test specimen; CuCr1Zr prototype A with a single-channel design; and CuCr1Zr prototype B with a gyroid-structure design.

Acknowledgements

The authors would like to express their sincere gratitude to the colleagues at GSI Darmstadt—Prof. Dr. R. Aßmann, Dr. U. Weinrich, Dr. G. Walter, Dr. M. Heilmann, Dr. R. Gebel, A. Bardonner, N. Shurkhno, M. Romig, S. Teich, R. Erlenbach, U. Laumann, M. Uhlig, N. Kähne, M. Henke, Dr. A. Schnase, Dr. A. Seibel, and Dr. C. Kleffner—, at IAP Frankfurt—Prof. Dr. H. Podlech,

S. Wagner, J. Storch, and D. Bänsch—, and at FZ Jülich— Dr. R. Stassen, Dr. F. M. Esser,H. Schneider, B. Poschen, B. Cramer, W. Lesmeister, S. Baier — for their valuable support and help. Special thanks are extended to the GSI Mechanical Workshop and the GSI Technology Lab for their professional contributions.

First pulses on test cavity with new MTCA-based digital LLRF system for UNILAC upgrade

Head: Dr. Gerald Schreiber (GSI)

Authors: C. Weickhmann, L. Meise

In preparation for the UNILAC upgrade program, the analogue low-level RF control systems are to be replaced by a digital low-level RF control system [8], based on the MicroTCA form factor. The RF system is based on a SIS8300KU FPGA-board (AMC) combined with a DS8VM1 front-end board (RTM) manufactured by Struck Innovative Systems GmbH.

The present work uses DESY's FWK/ChimeraTK framework for accelerated hard- and software development [9]. Started in 2022, the work has converged into a functional firmware and rudimentary expert user interface.

White Rabbit timing is provided through the FAIR Timing Receiver (FTR) [10]. The UNILAC "Phasenachse" is used as source for coherent digital down-conversion on the input side and for driving a vector modulator on the DS8VM1 board at the output.

The functionality is demonstrated using a buncher cavity originally developed for Cryring tuned to $f_0 = 108.408$ MHz and $Q \approx 2100$. The vector modulator output is pre-amplified using two Minicircuits 17 dB solid state amplifiers, driving a Rohde&Schwarz 50W power-amplifier (the type used in all movable amplifier chains as first stage).

The controller firmware implements an amplitude and phase PI-controller based on highly parametrised IIR SOS blocks that would generally allow many other controller topologies. Furthermore, it allows to apply a pre-emphase to the output signal which allows to counter the highly non-linear amplifier response. Arbitrary pre-emphase curves can be used. In this demonstration, however, a gamma correction curve of the form $y = x^\gamma$ with $x, y \in [0; 1]$ was used.

Figure 127 shows the measured powers at the amplifier input ("Vector Modulator Output"), at the 50W-Amplifier output towards the cavity and at the cavity probe. γ was varied to obtain a cavity probe signal that fits a straight line in log-log representation as closely as possible. $\gamma = 0.6$ fulfilled this requirement. Lower values were tested ($\gamma = 0.4$ and 0.5), but resulted in rather high instabilities, particularly in the lower amplitude range due to the increased effective loop gain.

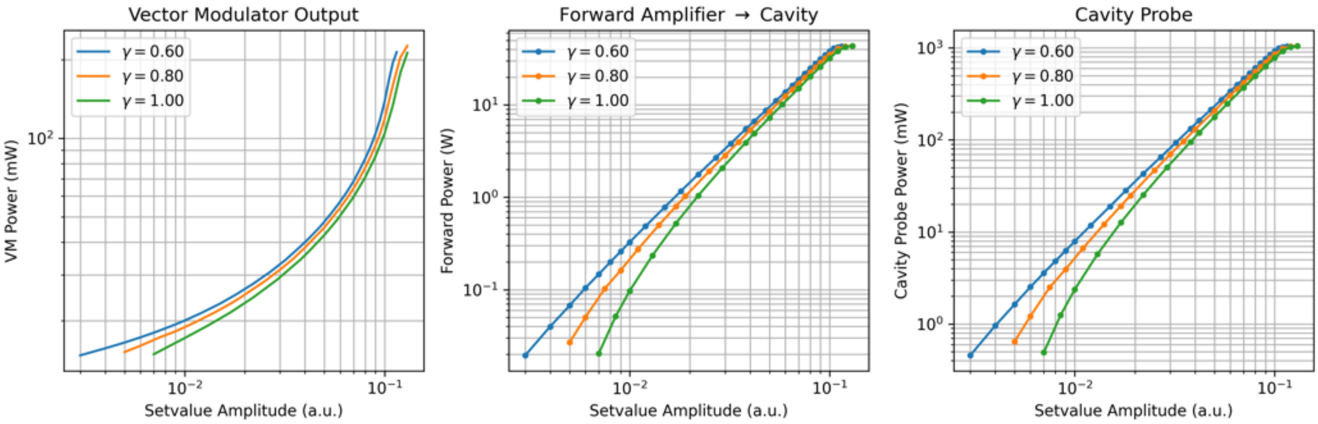

Figure 127: DS8VM1 Vector modulator output of the controller after the two Minicircuits 17 dB SSAs is measured (left). Forwarded Power into the cavity after 50W power-amplifier (mid) and the corresponding pickup power with unknown coupling factor (right). All measurements are carried out at three different γ values. The cavity was tuned to never return more than 0.4% of the forward power.

The system was used to drive the cavity to a user-defined power level at the pickup for amplitude measurement, subsequently called *probe power*. In Figure 128 the probe power of 500 mW was set for various values of γ, showing the improvement of the error signal of the controller. Controller parameters (P and I coefficients in this case) can be updated on the fly.

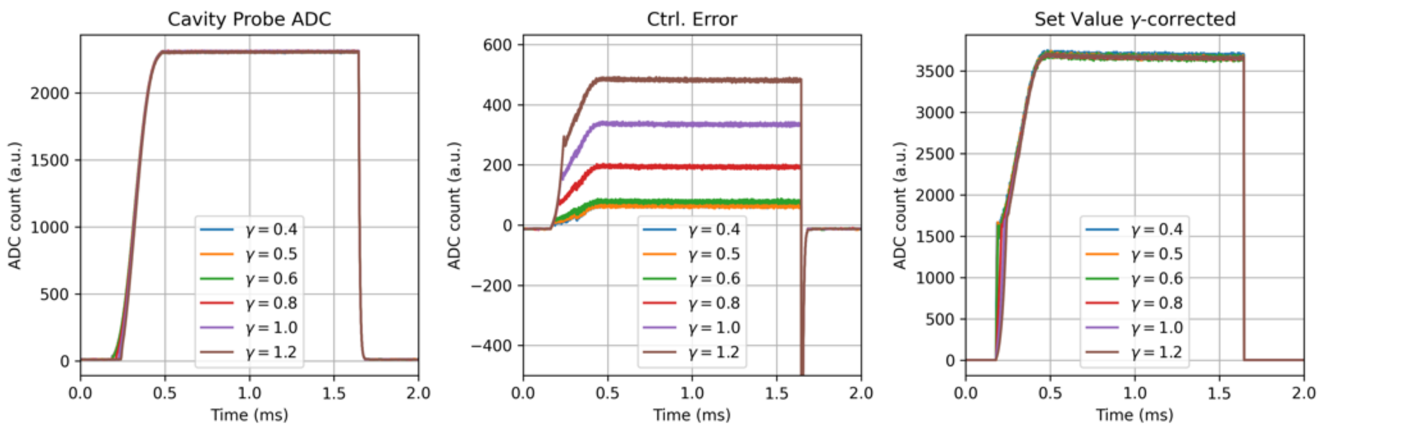

Figure 128: ADC sampled pickup signal from cavity with a measured power of 500 mW (left). Changing gamma values resulting in different error from the controller which tend to a minimum for lower gamma values (mid). The γcorrected set values are nearly identical to yield the desired tank amplitude (right).

Besides, a new concept for ω_0 controller was evaluated: the system continously measures the phase drift after the end of the RF pulse, i.e., when the cavity signal decays. This allows to directly drive the stepper motors of the plungers into resonance.

The results of early 2026's tests on the E5 single gap resonator and 150 kW amplifier chain reaching regulated output powers of 40 kW will be covered in next year's report.

Experimental Determination of Beam Emittance of the HLI Injector

Head: Uwe Scheeler (GSI)

Authors: P. Häckel M. Miski-Oglu, W. Barth, F. Dziuba, V. Gettmann, J. List, T. Kuerzeder, U. Scheeler, H. Vormann, S. Yaramyshev, N. Schmitt

To ensure good beam operation of the first cryogenic module, CM1 (cw Demonstrator in IMG4.1) of HELIAC, a digital twin was created to support operators with additional information such as the beam envelope or the particle distribution at different positions along the cryogenic module. The digital twin requires a realistic and accurate particle beam that arrives from the HLI.

We present the reconstruction of the six-dimensional particle distribution at the output of the HLI by using backtracking algorithms (transverse reconstruction) of transverse slit-grid emittance measurements and longitudinal tomography of Feschenko Bunch-Shape-Monitor measurements. The beamline setup is shown in Figure 129 and contains beam diagnosis elements.

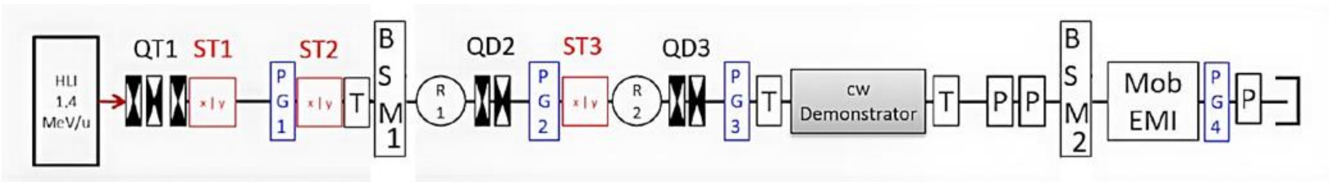

Figure 129: Overview of the current beamline setup. It contains Quadrupoles (QT/QD), Steerer magnets (ST), Profilegrids (PG), Bunchers (R), Transformers (T), BunchShapeMonitors (BSM), PhaseProbes (P) and Slit-Grid Measurements (EMI). The cw Demonstrator is the first cryomodule that is tested and simulated.

Figure 130 shows the reconstructed particle distribution in the XX' and YY' transversal planes of 6d phase space. The distribution in the YY' plane indicates that the beam has a non-Gaussian shape. The centroids of these distributions are not centred around zero, and it indicates that the beam enters the GUN6 beamline obliquely.

The calculated beam profiles, using these reconstructed distributions as input parameters for the simulation, show high agreement with measured beam profiles on SEM grids. The agreement holds for the setting of quadrupole lenses, which confirms high fidelity of reconstructed distributions.

The longitudinal reconstruction required BSM measurements. To achieve a high accuracy of tomographic reconstruction, a total of 40 longitudinal profiles were measured for 40 different buncher voltages. The resulting particle distribution shows either two or even three different centres of intensity maxima, indicating that there is not one but rather multiple beams with slightly different energies exiting the HLI injector. Approximately 30% of the particles have an energy deviation of more than 1.6 keV/u, and the cores have a difference in energy of about 4 keV/u. This result is also confirmed by measurements performed with FFC (Fast-Faraday-Cup). Figure 131 shows a lambda - shaped distribution in the XZ plane, indicating the presence of two beamlets with different energies inside the beam.

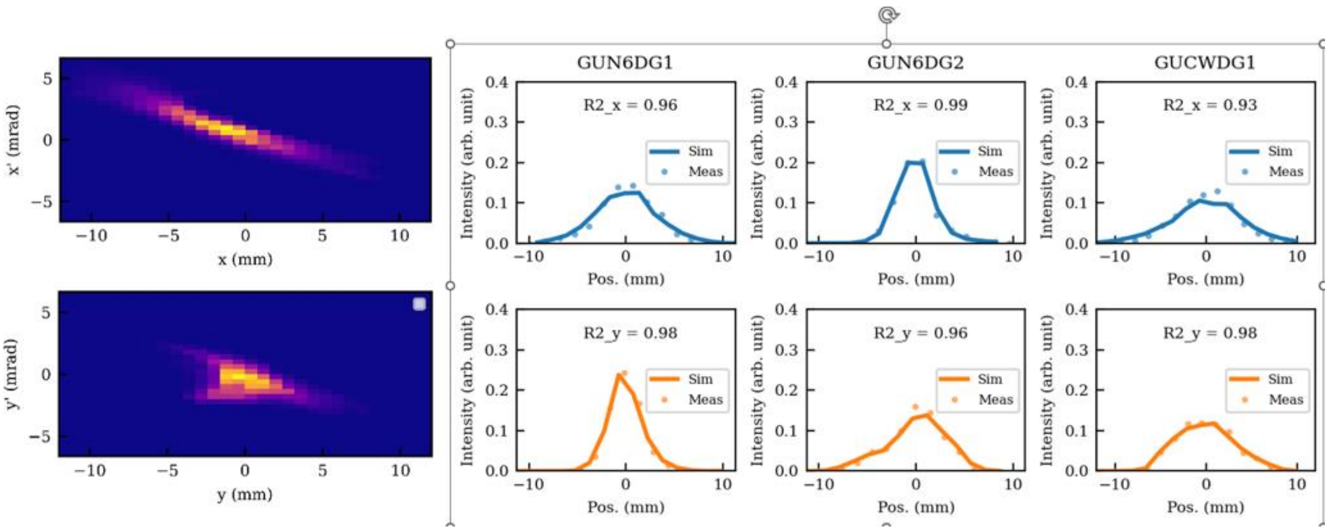

Figure 130: Showcase of the transverse reconstruction and simulation validation. The left shows the 2D projections of the reconstructed particle distributions. The right demonstrates the agreement between simulation and profile-grid measurements after changing quadrupole parameters.

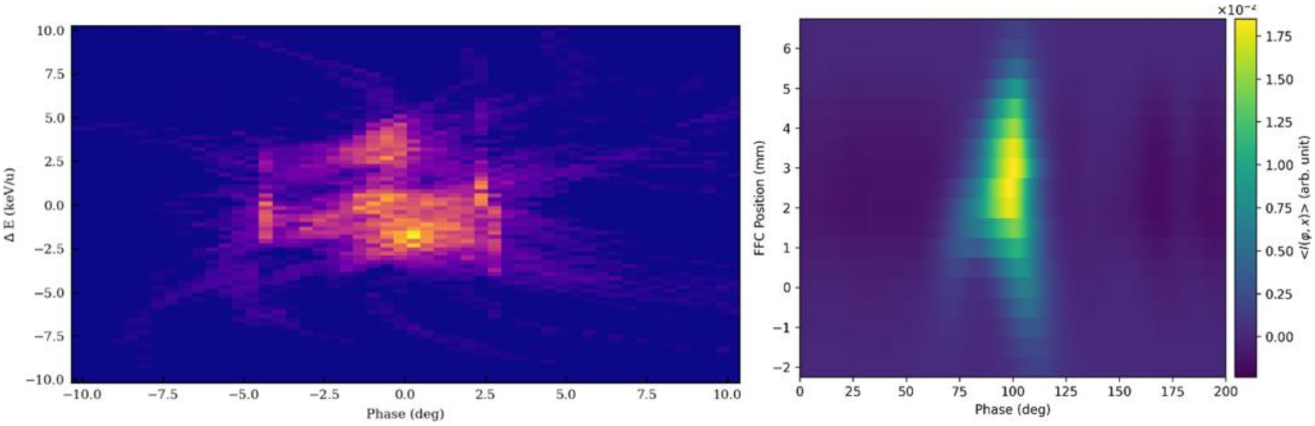

Figure 131: Showcase of longitudinal reconstruction (left) and FFC measurement (right). Left shows multiple beam centre intensity maxima indicating multiple beams with slightly different energies.

Experimental determination of the longitudinal emittance of the UNILAC beam using a fast Faraday cup

Head: Uwe Scheeler (GSI)

Authors: N. Schmidt, W. Barth, S. Klaproth, M. Miski-Oglu, P. Forck, R. Singh

In 2025, several campaigns were conducted to determine the bunch length and longitudinal emittance of the UNILAC beam. Using a Fast Faraday Cup (FFC) in X2, a beam run with $^{208}Pb^{26+}$ and $^{40}Ar^{8+}$ was performed in March and another beam run with $^{40}Ar^{8+}$ in July. The Fast Faraday Cup offers a highly accurate time-resolved recording of the charge distribution along the bunch. The FFC is located in X2 in a dispersive region, which means that particles with different energies are deflected differently. This causes the energy spread of the bunches to be projected onto the horizontal plane.

The same diagnostic chamber contains a SEM grid, which was used to determine the dispersion. The dispersion was measured by specifically varying the beam energy using the BE10 single gap resonator and measuring the corresponding horizontal deflection of the beam profile on the grid. The result is shown in Figure 132.

The FFC was used to measure the longitudinal charge distribution bunch-to-bunch along the macropulse. During the beam time in July, periodic fluctuations in amplitude with frequencies of 61 kHz and 490 kHz were detected, as can be seen in Figure 133. Its origin is not yet clear. This should be investigated during the next beam time.

To measure the entire beam, the FFC was moved horizontally through the beam using a stepper motor, whereby the beam was cropped due to the 0.8 mm opening of the FFC. Such a measurement can be found in Figure 134. The individual measurements at the horizontal positions can be assigned to a certain beam energy by means of the dispersion measurement, with higher position values corresponding to higher-energy particles. It should be noted that small phase values correspond to early arrival times.

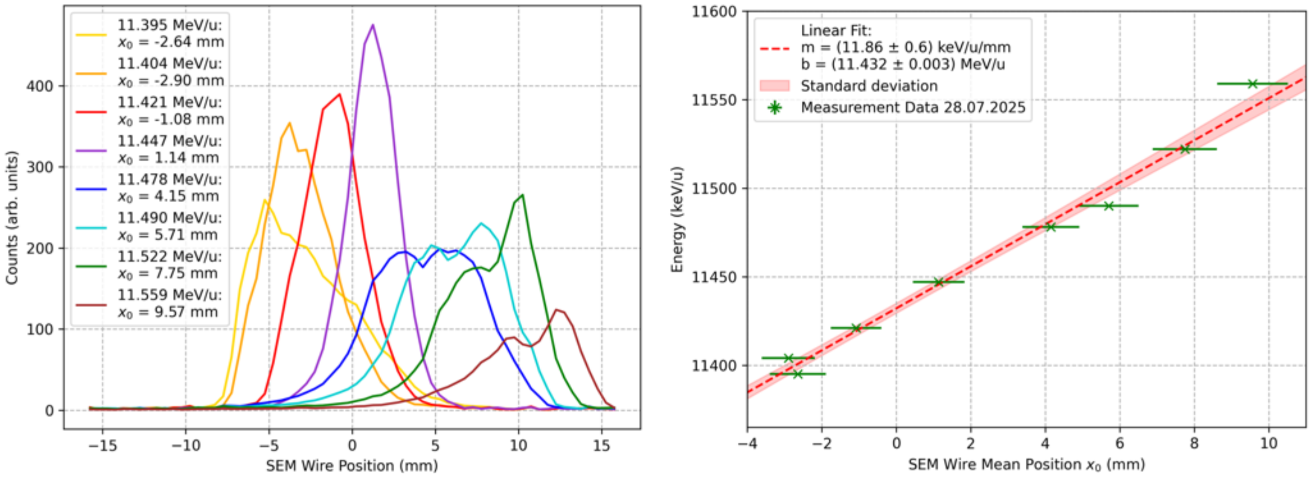

Figure 132: Secondary Electron EMission Grid (SEM-Grid) measurements for the dispersion evaluation in the X2 cave.

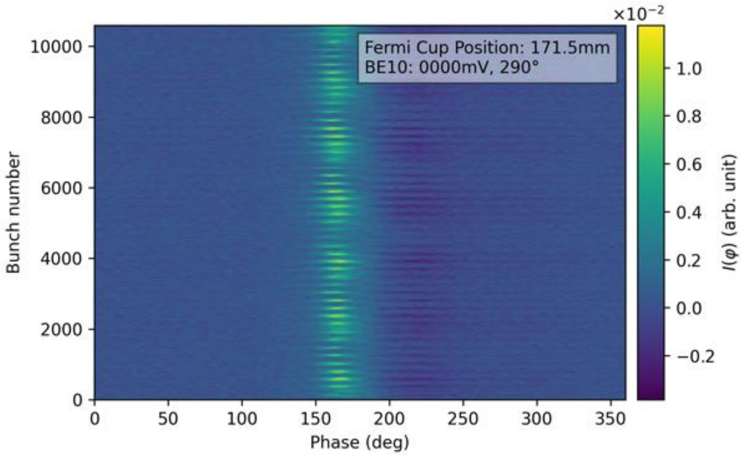

Figure 133: The longitudinal charge distribution along the macro pulse of a 35μA $^{40}Ar^{8+}$ in the X2 cave at the UNILAC.

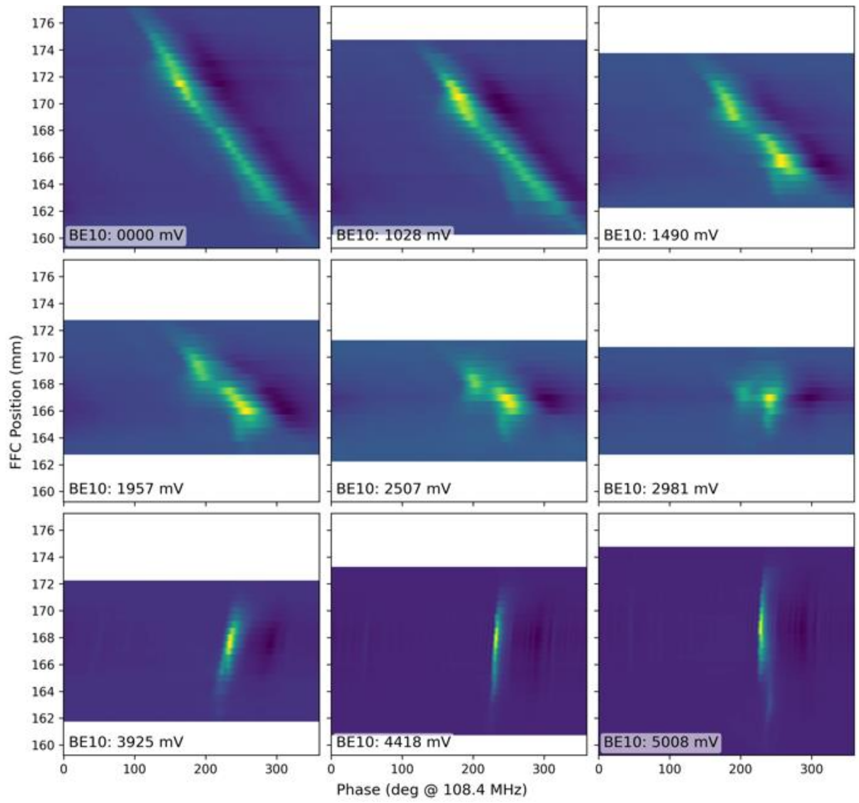

Figure 134: Longitudinal phase space measurements for different buncher amplitudes in bunching mode. The axes range in all plots is the same.

In order to test and verify the possibility of beam manipulation, the single gap resonator BE10 was set to be in bunching mode and the amplitude was gradually increased. For each of these dedicated settings, the entire beam was scanned horizontally with the FFC to measure the longitudinal phase space distribution. A selection of the measurements obtained through this method are presented in IMG5.3. The results reveal two distinct central energy peaks that require further investigation. Analogous measurements were conducted at the HLI by Pascal Häckel, wherein a distribution exhibiting multiple peaks was also observed.

It is evident from the data set that there is a clear and perceptible evolution of the distribution with increasing buncher amplitudes, confirming the validity of the method. The analysis of the measurement data and the subsequent determination of the longitudinal emittance remain to be completed and will be continued in the next phase of this work. As a first step, the recorded data will be validated and systematically compared with the underlying theoretical model. In addition, the measured longitudinal phase space distributions will be back-tracked to the exit of the Alvarez cavities. This reconstruction is required to determine the intensity distribution in the longitudinal phase space at that location and to enable a reliable interpretation of the beam properties at the cavity exit.

First co-circulation of heavy-ion beams in the ESR

Head: Dr. Bernd Alfrad Lorentz (GSI)

Authors: S. Litvinov, R. Hess, R. Joseph, C. Krantz, B. Lorentz, A. Sherijan, M. Steck†

† Deceased.

During slow collisions of co-circulating heavy ions near the Coulomb barrier, transient quasi-molecular states may form, enabling electron exchange and, for systems with a total charge exceeding the critical value Z≈173, the creation of supercritical fields leading to spontaneous electron-positron pair production from the vacuum [11].

A conceptually elegant way to realize such collisions in a storage ring is to store two beams on the same closed orbit with equal magnetic rigidity but different velocities [12]. This scheme became experimentally feasible at the ESR in 2025 following the implementation of the new LSA control system [13].

A convenient realization is the storage of two charge states of the same ion species, requiring only a single ion source. After acceleration in SIS18, the charge state is selected in the TE-line stripper. The magnetic rigidity downstream of the stripper and in the ESR is fixed for the first beam, while the extraction energy of the second beam from the SIS18 is adjusted such that $B\rho 1 = B\rho 2$, ensuring co-circulation on a common orbit.

For this purpose, two operationally identical ESR cycles were configured to inject the beams sequentially without ramping down the ring. The injection kicker pulse length was shortened to allow injection of the second beam while the first remained stored.

The proof-of-principle experiment was performed with bare $^{197}Au^{79+}$ and H-like $^{197}Au^{78+}$ beams at injection energies of about 407 and 400 MeV/u, respectively. Because independent bunching and simultaneous cooling are presently not possible, studies were carried out with coasting, uncooled beams. Co-circulation on a common orbit was confirmed by simultaneous scraping in the straight section of the ESR.

The scheme was subsequently applied to bare $^{238}U^{92+}$ and H-like $^{238}U^{91+}$ beams at 400 and 393 MeV/u, respectively. As for gold, simultaneous scraping verified the common orbit (see Figure 135).

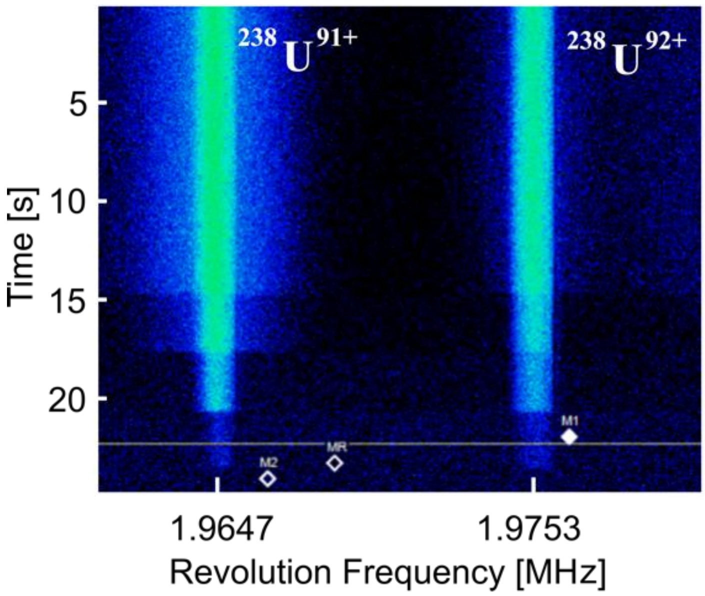

Figure 135: Schottky spectra of bare $^{238}U^{92+}$ and H-like $^{238}U^{91+}$ coasting, uncooled beams stored at the same time in the ESR. Both beams were removed together by stepwise inward movement of the scraper. The distinct revolution frequencies correspond to their different velocities.

In both cases, the difference in beam energies was insufficient to approach the Coulomb barrier (≈ 630 MeV for Au and ≈ 810 MeV for U). The resulting centre-of-mass collision energies were only about 3 MeV. To exceed the barrier within the co-propagating scheme, substantially larger energy differences and lower charge states would be required. For uranium, for example, combining $^{238}U^{92+}$ and $^{238}U^{78+}$ at approximately 392 MeV/u and 295 MeV/u would yield a collision energy slightly above the barrier (≈ 695 MeV). Multi-electron configurations, however, may influence electron-exchange processes. An alternative approach for bare or H-like ions, proposed in [14], is to circulate the beams on different closed orbits so that they intersect at a defined interaction point created by a special ESR optics, where the dispersion crosses the reference orbit in the straight section. This allows localised collisions and detector placement, in contrast to co-propagating beams interacting along the full ring.

Uranium front-to-end simulations for the existing and an upgraded UNILAC

Head: Dr. Lars Groening (GSI)

Authors: A.Rubin, X.Du, L.Groening, C.Xiao

Abstract

A dedicated uranium front-to-end simulation campaign has been conducted in order to compare performance along the 270 m beamline - from the northern source extraction gap to the SIS18 injection septum - for both the existing and upgraded UNILAC designs. The study focused on evaluating beam quality in terms of FAIR requirements, particularly emittance growth, beam brilliance, particle current, and momentum spread. The current UNILAC design cannot provide for FAIR's horizontal brilliance. However, the proposed upgrades successfully achieve these targets.

Description of the beam line

Simulations in both cases start from distributions measured in 2013 right after the northern source extraction gap. A virtual charge separator was used to extract the U^{4+} beam from the data [15]. The realistic particle distribution has been transferred through all UNILAC sections. The beam line comprises about 1200 elements (drifts, quadrupoles, dipoles, RF-gaps, stripper, slits etc.) with their parameters. Lattices are set to best performance within respective technical limits.

The main upgrade measures towards brilliance increase concern HSI MEBT and Alvarez DTL. Today's MEBT consists of one doublet and super lens, which should provide injection into sensitive KONUS IH-DTL section. Small apertures and just four knobs for matching of six parameters make this transport not adequate. The new proposed solution with two triplets and a buncher could provide significantly better performance.

The existing Alvarez DTL operates with too weak quadrupoles gradients, and the correspondent phase advance of σ_0 = 45° touches disturbing space charge resonances. Inter cavity sections without bunchers cause longitudinal mismatch. Alvarez 2.0 with sufficiently stronger quadrupole gradients (σ_0 = 65°) and optimised inter-tank sections provides significantly better beam transport with respect to FAIR requirements.

Main results of the front-to-end simulation

One of the most important criteria for the beam quality estimation along the line is horizontal brilliance (beam current/hor. emittance). At RFQ output its value for the existing and the upgraded UNILAC is similar. Significant differences of brilliance-changes appear along the HSI MEBT (and correspondently IH-DTL), matching to post-stripper, and post-stripper DTL. Today's brilliances may be doubled by just replacing the HSI MEBT section (see Figure 136).

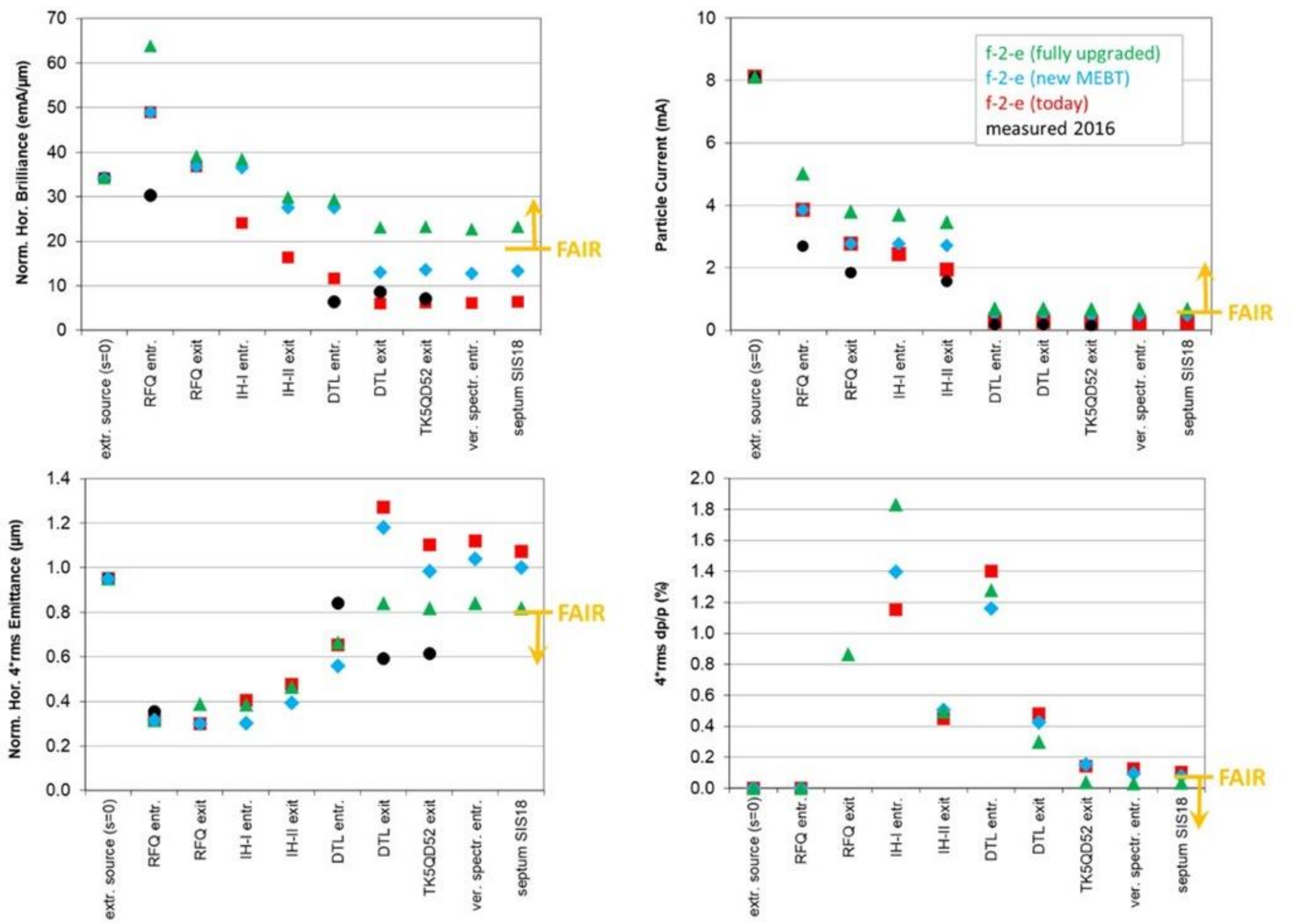

Figure 136: Horizontal brilliance (left, top), particle current (right, top), horizontal emittance (left, bottom) and pulse spread (right, bottom) along front-to-end beam line for the existing (red dots) and fully upgraded (green dots) UNILAC. Blue dots show the case of existing UNILAC with new MEBT. Black dots correspond to measurements from 2016.

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12. Annex

12.1 GSI and FAIR committees in the year 2025

Compiled by T. Beier & K.Füssel

Director's Board / Geschäftsführung

- Scientific Managing Director: Prof. Dr. Thomas Nilsson
- Administrative Managing Director: Dr. Katharina Stummeyer
- Technical Managing Director: Jörg Blaurock

Shareholder Assembly / Gesellschafterversammlung, GSI

- Stephanie Jörres, Bundesministerium für Forschung, Technologie und Raumfahrt (Germany), as chair and representative of the Federal Republic of Germany
- Dagmar Brinkmann, Finanzministerium Hessen (Germany), as representative of the State of Hesse in Germany
- Bernd Biron, Finanzministerium Rheinland-Pfalz (Germany), as representative of the State of Rhineland-Palatinate in Germany
- Morris Gilles, Finanzministerium Thüringen (Germany), as representative of the State of Thuringia in Germany.

Supervisory Board / Aufsichtsrat (AR), GSI

- Volkmar Dietz [chair], Bundesministerium für Forschung, Technologie und Raumfahrt (Germany) – until 14.9.2025
- Andrea Fischer [chair], Bundesministerium für Forschung, Technologie und Raumfahrt (Germany) - member since 15.9.2025, chair since 13.11.2025
- Ralph Dieter, Bundesministerium für Forschung, Technologie und Raumfahrt (Germany) – until 14.9.2025
- Andreas Gerhardt, Ministerium für Wissenschaft und Gesundheit des Landes Rheinland-Pfalz, Mainz, (Germany)
- Marialuisa Aliotta, University Edinburgh (UK), as Vice-Chair of the Joint Scientific Council GSI/FAIR
- Thomas Glasmacher, Facility for Rare Isotope Beams, East Lansing (USA)
- Cornelia Denz, Physikalisch-Technische Bundesanstalt (Germany)
- Bettina Lommel, GSI Helmholtzzentrum für Schwerionenforschung, as spokesperson of the Scientific-Technical Council of GSI

FAIR Council / Gesellschafterversammlung FAIR

- Catarina Sahlberg [chair], Swedish Research Council (Vetenskapsrådet) (Sweden)
- Volkmar Dietz [vice chair], Bundesministerium für Forschung, Technologie und Raumfahrt (Germany) - until 31.8.2025
- Andrea Fischer [vice chair], Bundesministerium für Forschung, Technologie und Raumfahrt (Germany), since 1.9.2025
- Dirk Steinbach, Bundesministerium für Forschung, Technologie und Raumfahrt (Germany), as representative of the Federal Republic of Germany
- Christine Burtscheid, Hessisches Ministerium für Wissenschaft und Forschung, Kunst und Kultur (Germany), as representative of Hesse, Germany
- Maxim V. Bogachev, Rosatom Nuclear Energy State Corporation, as representative of the Russian Federation
- Victor Yu. Egorychev, NRC Kurchatov Institute, as representative of the Russian Federation
- Kaustuv Sanyal, Bose Institute, as representative of India
- Praveeenkumar Somasundaram, Department of Science and Technology, as representative of India
- Katri Huitu, Helsinki Institute of Physics, as representatives of the Swedish/Finnish Consortium
- Sofie Björling, Swedish Research Council (Vetenskapsrådet), as representatives of the Swedish/Finnish Consortium
- Cornelia Anca Ghinescu, Ministry of Research, Innovation and Digitalisation,

as representative of Romania
- Ruxandra Popescu, Ministry of Research, Innovation and Digitalisation,
as representative of Romania
- Piotr Salabura, Jagiellonian University Kraków,
as representative of Poland
- Michal Goszczyński, Department of Innovation and Development of the Ministry of Science and High Education,
as representative of Poland
- Albin Kralj, Ministry of Education, Science and Sports,
as representative of the Republic of Slovenia
- Danielle Gallo, Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA),
as representative of the French shareholder CEA
- Marcella Grasso, Centre National de la Recherche Scientifique (CNRS),
as representative of the French shareholder CNRS
- Helen Beadman, UK Research and Innovation - Science and Technical Facilities Council (UKRI - STFC),
as representative of the United Kingdom
- Marek Vyšinka, Ministry of Education, Youth and Sports (MSMT),
as representative of the Czech Republic
- Andrej Kugler, Nuclear Physics Institute of the Czech Academy of Sciences,
as representative of the Czech Republic

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Scientific Secretary: Thomas Beier - until 30.9.2025; Inti Lehmann – since 1.10.2025
Deputy Scientific Secretary: Inti Lehmann – until 30.9.2025; Jennifer Steitz - since 1.10.2025

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Scientific Secretary: Thomas Beier.

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Scientific Secretary: Monica Wamers.

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Scientific Secretary: R. Böhm.

12.2 Organisational charts

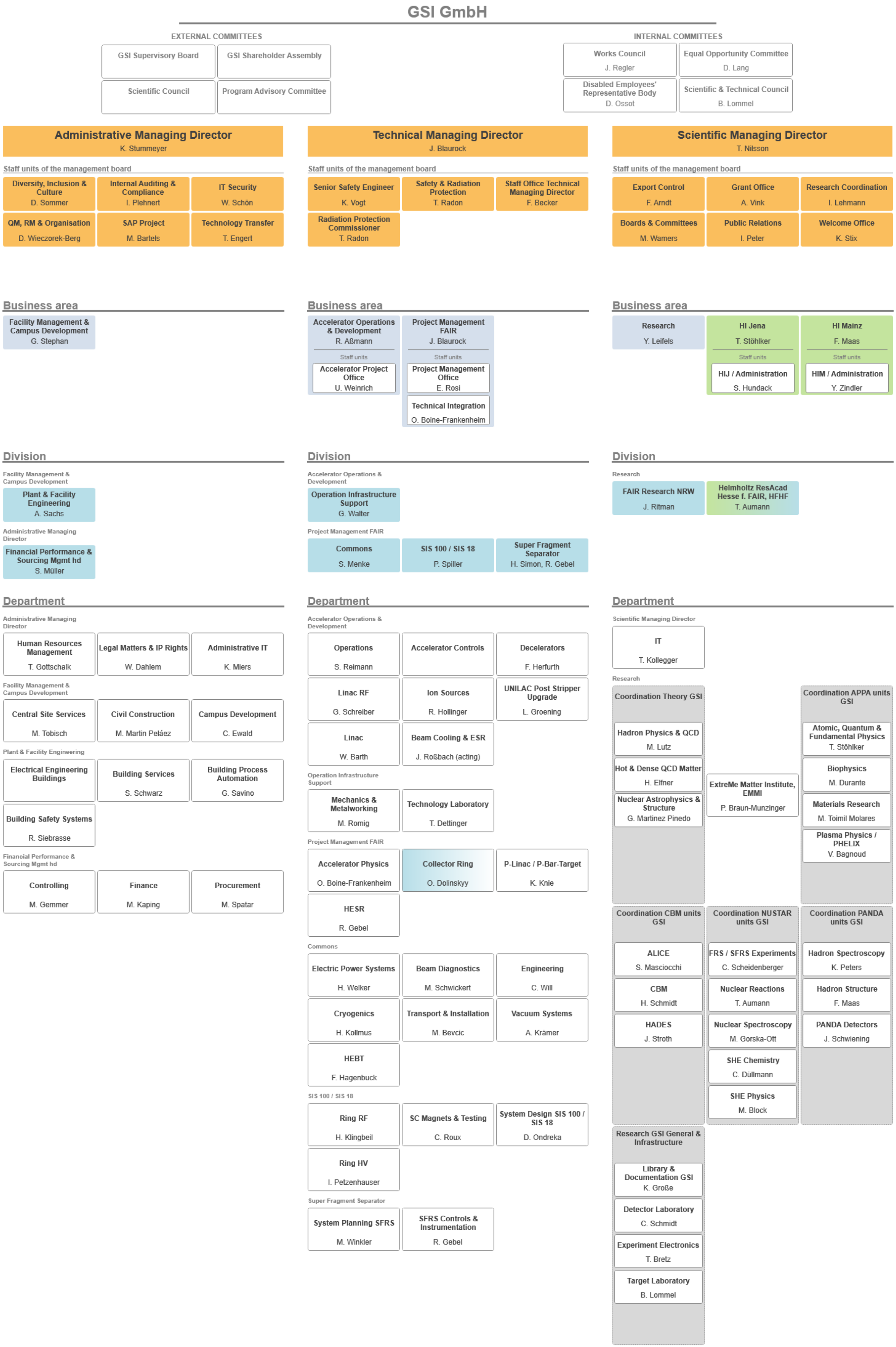

Figure 137: GSI organigram.

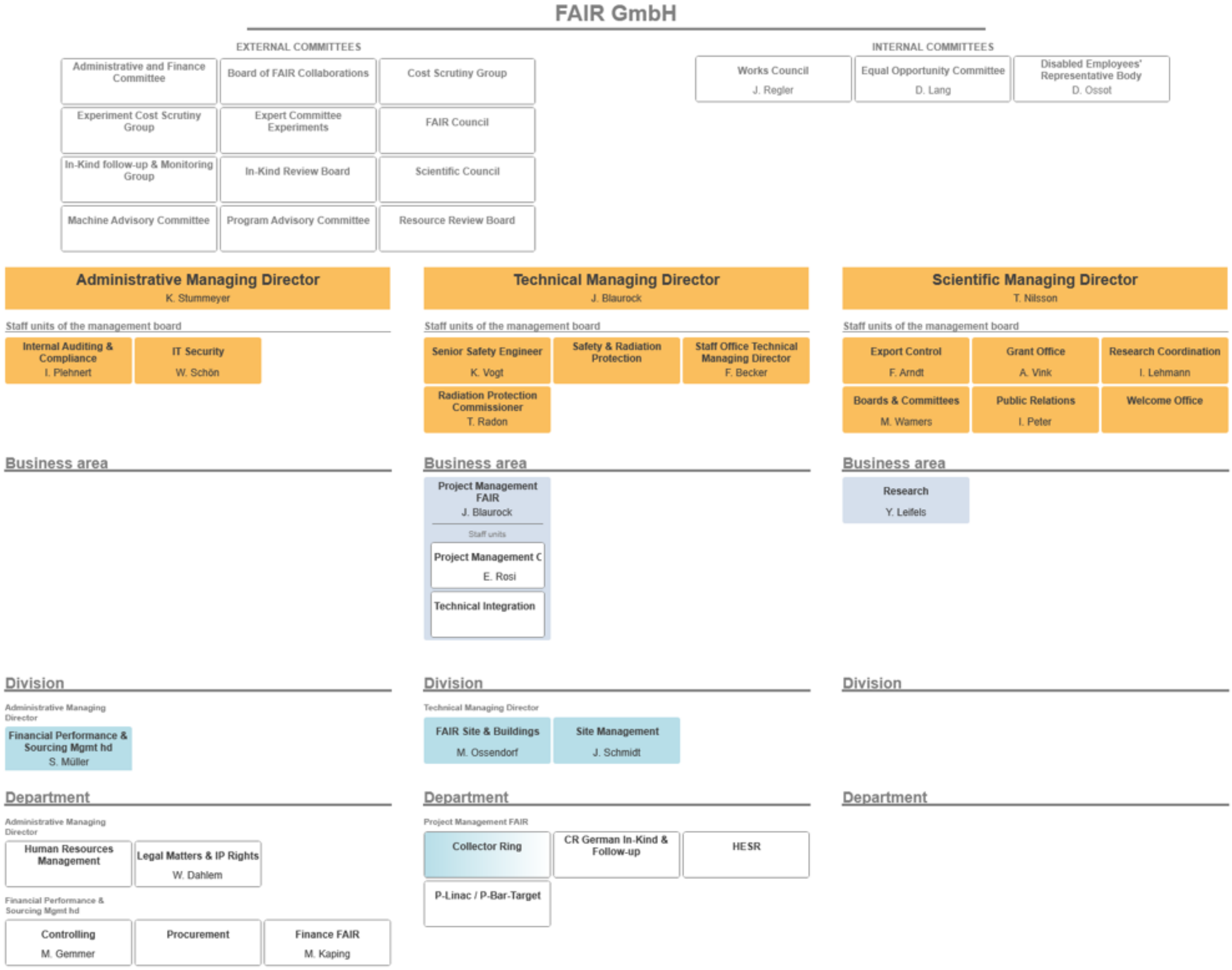

Figure 138: FAIR organigram.

GSI is a member of the largest national non-university science organization, the Hermann von Helmholtz Association of German Research Centres (e.V.), in the contributions to solve big and pressing questions of society, science and economy in a total of six research areas: energy, earth and environment, health, key technologies, matter, traffic and space. GSI is researching in the research field of matter of the program-oriented research of the Helmholtz Association. At the GSI, basic research is applied, but also application-oriented research in the disciplines of hadron and nuclear physics, nuclear astrophysics, atomic physics, plasma physics, materials research as well as biophysics, radiation biology, space research, and medical technology.

GSI Helmholtz-Zentrum für Schwerionenforschung GmbH operates a worldwide unique one accelerator system for ion beams with adjoining experimental equipment. The purpose of GSI is to promote science and research, in particular through the development, construction and operation of accelerator systems for Hadron and ion beams as well as basic and applied research on the areas of science, materials science, and life sciences. For the future sees GSI the realization and use of the Facility for Antiproton and Ion Research (FAIR) in international cooperation as the most urgent goal. Partners of GSI are the Federal Republic of Germany with 90%, the country Hesse with 8%, the Free State of Thuringia with 1% and the Land Rhineland-Palatinate with 1% shares. The Helmholtz institutes in Jena and Mainz become 90% external branches of GSI funded by the federal government and 10% by Thuringia and Rhineland-Palatinate. On behalf of the German Federal Ministry of Research, Technology and Space (BMFTR), the GSI is German Shareholder of the Facility for Antiproton and Ion Research in Europe, founded in 2010 GmbH (FAIR GmbH), in cooperation with nine partner countries - Germany, Finland, France, India, Poland, Romania, Russia, Sweden, and Slovenia - as well as the United Kingdom as associated partner - first the construction and later the operation of the FAIR plant in Darmstadt is tracked.