GSI REPORT 2025-1

GSI-FAIR SCIENTIFIC REPORT 2024

An overview of the 2024 achievements in science and technology

FAIR Phase-0 Research Program

GSI FAIR
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Cover page illustration: A major milestone was the start of the installation activities in the tunnel of the SIS100 accelerator in Early 2024; the first SIS100 supra-conducting dipole modules and some HEBT magnets have been brought down to the SIS100 tunnel and placed along the beamline.

Photograph: Peter Spiller (GSI)

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An overview of the 2024 achievements in science and technology

Imprint

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

Editors: Arnaud Le Fèvre, Yvonne Leifels.

Printed by Druck- und Verlagshaus Knittel,
Darmstadt, Germany

Publication date: August 2025
GSI Report 2025-1, DOI: 10.15120/GSI-2025-00806, license: ccby4
Contact: gsilibrary@gsi.de

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1. Executive summary of research at GSI & FAIR

Coordination: Dr. Yvonne Leifels (GSI)

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

1.1 Research and technical developments at GSI/FAIR

Author: Yvonne Leifels.

In 2024, GSI and FAIR entered a new phase of leadership. In June, Dr. Katharina Stummeyer, a Biochemist and science manager, started her position as new Administrative Director of GSI and FAIR. She previously has been head of the project management agency for Reaktorsicherheit (GRS). Dr. Stummeyer succeeded Dr. Ulrich Breuer, who accepted the position of chancellor at the Goethe University Frankfurt. Later this year, in December, Prof. Dr. Thomas Nilsson took office as the the new Scientific Managing Director. A prominent experimental nuclear physicist, he previously served as a professor at Chalmers University of Technology in Gothenburg, Sweden, and was actively involved in FAIR's scientific planning from its early stages. He also held key leadership roles within major European collaborations.

The GSI/FAIR community also extended its heartfelt gratitude to Prof. Dr. Paolo Giubellino, whose term as Scientific Managing Director concluded in June 2024. Under his guidance, GSI/FAIR achieved numerous scientific milestones and made decisive progress in the realization of the FAIR project. He has now taken on a new leadership role as President of Scientific Commission III at the Italian National Institute for Nuclear Physics (INFN), which oversees the national research program in nuclear physics in Italy.

The FAIR Phase-0 beam time block from beginning of February to end June 2024 comprised 108 days of physics user beam time. The beam time block included a broad scientific program from all research areas. The UNILAC beams were mainly used by SHE and materials research experiments. SIS18 served, with direct beams and secondary beams via the fragment separator, a broad user community of NUSTAR and CBM/Hades. In addition, bio- and plasma physics user groups were served. For the SPARC community, beam time was provided at ESR and CRYRING, which partly was operated with an internal ion source and injector. Overall, nine different NUSTAR FAIR Phase-0 experiments have been performed at the FRS. Each experiment has an individual science goal, uses a dedicated setup and often a specially-tailored ion-optical setting, and requires a specific data acquisition system. Financially the travel and subsistence of many experimentalists could be supported by the group activities within the "EURO-LABS" Transnational Access program. In April 2024, the first ever ^{170}Er (erbium) beam produced at GSI was delivered to the FRS target. Selected fragmentation reaction products of the erbium beam were used by the DESPEC experimental setup. The High Acceptance Di-Electron Spectrometer (HADES) conducted experiments with gold-gold (Au+Au) and carbon-carbon (C+C) collisions at 0.8 GeV/u. The GSI accelerator team implemented a Digital Spill Optimization System (SOS) to enhance the beam quality during this experiment. This system achieved a 90% duty factor, significantly improving beam stability and data acquisition rates. The HADES experiments yielded the first measurements of Λ hyperons at such low beam energies, providing valuable insights into dense baryonic matter relevant to neutron star physics. Unfortunately, the cryogenic system of the HADES magnet failed during this beam time and the completion of the run had to be postponed to 2025. In addition, the HITRAP Decelerator was able to demonstrate ion deceleration and trapping for the first time after having spent substantial efforts in the technical improvements.

In November 2024, NuPECC launched the new Long Range Plan for nuclear physics in Europe emphasizing both fundamental research and societal applications. The importance of the FAIR facility was underlined and its timely completion and full exploitation stressed. FAIR is seen as central to European nuclear science, particularly for studying matter under extreme conditions, structure and reactions of exotic nuclei. Full support is recommended for all scientific pillars fo FAIR: APPA, CBM, NUSTAR, and PANDA. GSI played a significant and multifaceted role in shaping the NuPECC Long Range Plan 2024 (LRP2024), contributing both scientific expertise and strategic leadership. GSI scientists were active in several working groups addressing different topics, and GSI hosted key meetings during the LRP2024 development, including the Chapter Finalisation Meeting in February 2024, underscoring its central role in the planning process.

The European Research Council (ERC) awards Advanced Grants to support exceptional established researchers to pursue ambitious, high-risk research projects. Two GSI researchers have been successful in this year evaluation round in April. Thomas Stöhlker, head of the research department for Atomic, Quantum and Fundamental Physics at GSI/FAIR, Director of the Helmholtz Institute Jena and Professor at the Friedrich Schiller University Jena, receives an Advanced Grant for his project HITHOR, which aims to investigate highly charged 229-thorium ions to pave the way for the development of a nuclear clock. A nuclear clock would enable time measurement with unprecedented precision, with great potential for new insights into basic research and innovative applications. The grant to Prof. Dr. Stöhlker relies on the unique combination at GSI of outstanding scientist with breakthrough ideas and unique instrumentation and infrastructure. In particular, the GSI storage rings allow for unparalleled precision experiments with nuclear beams (HITHOR in this case). The consortium of Dr. Maarten Boonekamp (spokesperson, Institute of Research into the Fundamental Laws of the Universe, CEA, Paris-Saclay), Prof. Dr. Jens Erler (Institute for Nuclear Physics, JGU Mainz), and Prof. Dr. Frank Maas (Institute for Nuclear Physics, JGU Mainz, GSI/FAIR and Helmholtz Institute Mainz) has been awarded an ERC Advanced Grant for the project "Zeptometry". This project aims to combine new precision measurements at the highest LHC-energies at the European Organization for Nuclear Research CERN with challenging new precision measurements at very low energies with the upcoming MESA accelerator in Mainz in connection with the theory interpretation of the experimental results.

Sunday		Monday		Tuesday		Wednesday		Thursday		Friday	
5:30 pm - 6:00 pm	**Get Together**	8:45 am - 10:45 am	**Opening Session**	8:40 am- 11:55 am	**Presentation of GSI's Scientific Activities**	8:30 am - 9:30 am	**Marketplace on Strategic Topics**	8:40 am - 10:00 am	**Closed Session**	9:00 am - 11:00 am	**Final Closed Session**
6:00 pm - 7:00 pm	**Closed Session**	10:45 am - 11:00 am	**Coffee Break**	10:35 am - 10:50 am	**Coffee Break**	9:30 am - 9:40 am	**Coffee Break**	10:00 am - 10:10 am	**Coffee Break**	11:00 am - 12:00 pm	**Initial Notification of Review Results**
7:00 pm - 7:15 pm	**Get Together with**	11:00 am - 12:00 am	**Closed Session**	10:50 am - 11:55 am	**Presentation of GSI's Scientific Activities**	9:45 am - 10:45 am	**Closed Discussion with GSI Strategic Partners**	10:10 am - 11:00 am	**Closed Discussion with JSC**	12:00 am - 1:00 pm	**Lunch**
7:15 pm - 8:00 pm	**Opening Session (I)**		**Transport to HI Mainz**	12:00 am - 1:00 pm	**Closed Session**	10:45 am - 10:55 a	**FAIR Introduction**	11:00 am - 12:30 pm	**Closed Session**	2:00 PM	**End of Evaluation**
8:00 pm - 22:00 pm	**Dinner**	1:15 pm - 1:45 pm	**Light Lunch**	1:05 pm - 2:05 pm	**Discussion with Young Scientists**	10:55 am - 1:00 pm	**Guided Tours to FAIR**	12:30 pm - 1:30 pm	**Lunch**		
		1:45 pm - 4:10 pm	**Presentation of HI Mainz**	2:15 pm - 3:15 pm	**User Facilities**	1:00 pm - 1:40 pm	**Lunch**	1:30 pm - 3:00 pm	**Clarification of Remaining Questions**		
		4:10 pm - 4:20 pm	**Coffee Break**	3:15 pm - 6:30 pm	**Guided Tours to GSI Facilities**	1:45 pm - 3:30 pm	**Presentation of HI Jena**	3:00 pm - 7:00 pm	**Closed Session**		
		4:20 pm - 5:45 pm	**Guided Tours to Facilities**	6:30 pm - 7:30 pm	**Closed Session**	3:30 pm - 4:15 pm	**Poster Session Hi Jena**	7:30 pm - 9:00 pm	**Dinner**		
		5:45 pm- 6:45 pm	**Closed Session**	7:30 pm - 9:00 pm	**Dinner**	4:15 pm - 4:45 pm	**Coffee Break**				
			Transport to Darmstadt			4:45 pm - 5:30 pm	**Poster Session HI Jena**				
		7:45 pm - 9:00 pm	**Dinner**			5:30 pm - 7:00 pm	**Closed Session**				
						7:30 pm -9:30 pm	**Dinner**				

Table 1: Agenda of the center evaluation from April 6th to April 11th.

In addition, an ERC Starting Grant was awarded to Dr. Zewei Xiong. Dr. Zewei Xiong is currently working as postdoctoral researcher in the Nuclear Astrophysics and Structure department. His project "Neutrino flavor Transformations in dense Astrophysical Environments" is aimed to advance our understanding regarding the flavor evolution of neutrinos and their implication for particle and astrophysics.

Outlook 2025

As an intermediate step towards preparing the strategic proposals for the 5th Period of Program-Oriented Funding (2028-2034), a comprehensive scientific evaluation is performed at each of the 18 Helmholtz Centers assessing their scientific performance in the first part of PoF IV period within the research field(s), program(s), and topic(s) addressed by the respective center. For GSI the scientific review will take place during the period April 6th to April 11th, 2025. It will focus on GSI's research and development activities in the research field Matter from 2021 to 2023/24.

The review panel is to be composed of international high-caliber experts, who cover all aspects of the research activities of the center under review. As Chair Prof. Patricia Rossi, an internationally renowned nuclear physicist from Jefferson Laboratory was appointed by the Helmholtz Senate. The other 18 members of the Panel are nominated based on a shortlist of candidates in consultation with various stakeholders with expertise in the relevant fields.

The evaluation covers the recent 4 years. It is based on:

- written documents (structured in 2 Volumes)
- and a six-day on-site review including a visit of the Helmholtz Institute Mainz.

The schedule foresees a visit to the HI Mainz on April 7th with talks and facility tour, whereas the HI Jena presentation takes on April 9th at GSI. Introductory talks, a video presentation and an extended poster session give the reviewers a detailed insight into research at HI Jena. A tour of the GSI facilities and the FAIR construction site round off the review.

A detailed overview of the center review is shown in Table 1.

We wish for a successful, constructive, and forward-looking evaluation that strengthens GSI's scientific mission, secures future funding, and reaffirms its leadership in heavy-ion research and large-scale science infrastructure.

1.2 Beamtimes for scientific experiments in 2024

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	Durante, Marco	15	
B-ESA	ESA beamtime	Durante, Marco	10	
B-Radnext U	RADiation facility Network for the EXploration of effects for indusTry and research	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-22-00025	High-Resolution Electron-Ion Collision Spectroscopy of Berylliumlike Heavy Ions in CRYRING@ESR	Schippers, Stefan	28	
G-22-00028	Indirect measurements of neutron-induced reaction cross sections at storage rings	Jurado, Beatriz	22	
G-22-00034	Chemical studies of carbonyl complexes of the superheavy elements Sg (Z = 106) and Bh (Z=107)	Yakushev, Alexander	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-22-00072	Commissioning and First Storage Ring Experiments of the CRYRING Transverse Electron Target (Resubmission of Proposal E149)	Brandau, Carsten	36	
G-22-00073	Matter radius of the hyperhalo candidate $^{3}\Lambda$H from interaction cross-section measurements	Obertelli, Alexandre		7
G-22-00086	Ultra-high resolution study of the ^{15}O(α,α)^{15}O reaction using CARME@CRYRING	Bruno, Carlo	21	
G-22-00091	Probing nucleon-nucleon correlations in atomic nuclei via (p,pd) QFS reactions	Petri, Marina	20	
G-22-00092	Testing diamond detectors for development of an active target	Wimmer, Kathrin	7	
G-22-00095	Energy determination of the 1s2 2s1/2 → 1s2 2p3/2 radiative transition in Li-like uranium ions via resonant coherent excitation in crystal	Bräuning-Demian, Angela	16	
G-22-00100	Structure of neutron-rich, rare-earth nuclei far from stability	Albers, Helena	27	
G-22-00110	mCBM SIS18 2023/24 (and UNILAC Si Detector test)	Sturm, Christian	14	50
G-22-00111	Towards limits of nuclear structure by using a 9C beam	Chudoba, Vratislav		4
G-22-00117	In-cell multi-nucleon transfer reactions at the FRS Ion Catcher - a new perspective towards broadband heavy neutron-rich isotope studies with stable and unstable beams	Constantin, Paul	13	
G-22-00118	R3B - 2023 COMMISSIONING	Gernhäuser, Roman	6	6
G-22-00122	Symmetry energy at high densities from neutron/proton flow excitation functions	Russotto, Paolo	10	
G-22-00143	TEST of DESPEC Fibre Impanter (FIMP)	Vencelj, Matjaz	10	
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	48	10
G-22-00160	FRS developments for APPA and NUSTAR experiments: Performance improvements and R&D work with heavy-ion beams	Scheidenberger, Christoph	3	
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		13
G-22-00179	First test of MNT reactions with secondary beams at the FRS Ion Catcher	Mollaebrahimi, Ali	4	

Proposal number	Experiment topic	Spokesperson	Main shifts	Parasitic shifts
G-22-00180	Measurement of production cross sections of neutron-deficient fragments in the range of Z=82 to Z=89 in the reaction 238U+9Be	Grahn, Tuomas	6	
G-22-00181	Extending the quest towards the N=126 r-process waiting point	Reiter, Peter	17	
G-22-00182	Fission isomer studies with the FRS	Zhao, Jianwei	0	
G-22-00198	Absolute rate coefficients from dielectronic recombination for the astrophysically relevant ions Ne3+ and S3+ (Resubmission of G-22-00047)	Lestinsky, Michael	20	
G-22-00199	Target-electron correlations in slow-collision of ions with neutral targets	Ehresmann, Arno	24	
G-22-00200	Investigation of D+D fusion at BBN energies using CARME@CRYRING	Bruno, Carlo	30	
G-22-00201	A novel investigation of electron screening in low energy nuclear reactions using CARME@CRYRING	Marsh, Jordan	42	
M-CMAT	Materials Research at Cryring	Toimil-Molares, Maria Eugenia	0	
M-Radnet X0	RADiation facility Network for the EXploration of effects for indusTry and research	Toimil-Molares, Maria Eugenia		6
M-SMAT	Materials Research at SIS18	Toimil-Molares, Maria Eugenia	20	27
M-UMAT	Materials Research at UNILAC	Toimil-Molares, Maria Eugenia	102	123
P-0089	Particle acceleration in a laser-driven magnetized plasma	Gregori, Gianluca		14
P-0137	Detection of ion-beam heating induced melting and graphitization by laser-driven X-ray probing	Major, Zsuzsanna		55
T-SFRS Det. Tests	FAIR Super-FRS Detector tests	Nociforo, Chiara	5	

Table 2: List of user experiments in 2023 and accounted beamtime in 8h shifts. Secondary beam users get on the average 10% of the available beam time.

1.3 Developments for Research Data Management at GSI/FAIR

Author: Andrew K. Mistry

The diverse and complex data at GSI and FAIR requires good data governance, especially for managing research data. Whereas research outputs were once kept internal or within collaborations, Open Science is now driving a shift toward broader public access. GSI and FAIR strongly support these initiatives, and to that end are observer members of the European Open Science Cloud.

Progress is being made on Research Data Management (RDM) initiatives within GSI to realise this. These efforts are led by the GSI/FAIR Open Science Working Group, aiming to develop infrastructure, concepts, and documentation that are practical and beneficial for GSI/FAIR users. Recent outcomes include a set of RDM guidelines and a policy, as well as a dedicated webpage with further information available on the GSI website. Additionally, presentations and discussions are offered to research groups and collaborations, either by members of the Open Science Working Group—many of whom are active researchers—or by the Research Division.

Infrastructure development is being carried out by the IT department and the Research Division through national (e.g., PUNCH4NFDI) and international (e.g., OSCARS-NAPMIX) collaborative projects.

During the PoF IV period within the Helmholtz community, the focus is on examining and optimizing the methodology for the open publication of datasets, including tracking the number of data outputs within each institution. While this serves as a useful benchmark, adherence to the Findable, Accessible, Interoperable, and Reusable (F.A.I.R.)-principles.

Research Data Management Organiser

To support the management of research projects, the Research Data Management Organiser (RDMO) software has been made available. A catalogue has been implemented for GSI projects, allowing for a Data Management Plan (DMP) to be prepared in an easy and user-friendly way. A DMP outlines how research data is to be handled during the course of the project, including responsibilities, storage, publication, access rights and future preservation. It can be updated throughout the project lifecycle as changes occur.

A DMP is an effective way for good project management, enhances reproducibility by documenting data handling processes, and helps allocate resources efficiently. Additionally, a DMP supports open science initiatives by promoting data sharing and transparency.

It is strongly encouraged to prepare a DMP for any research project and is now requested as a part of beamtime acceptance.

Development of Metadata Schema

In 2024 GSI received support from the OSCARS project to develop a metadata schema for data publication in the experimental Nuclear, Astro, and Particle Physics fields (NAPMIX). This project will develop a standard for the European community and is in collaboration with FAIR, DESY, KIT, GANIL, US-CNA, LATR-IST, CNA-Seville, HUN-REN ATOMKI, Helmholtz Metadata Collaboration, HZDR, and TU Darmstadt. In addition to the metadata standard, the project will deliver a user-friendly application for generating metadata for specific datasets

A similar initiative has been ongoing in Plasma Physics, supported by the Helmholtz Metadata Collaboration. A workshop was held at GSI in 2024 including project updates.

Open Science work package within EUROLABS

Work progressed in the IT department on the creation of a data lake prototype for the EUROLABS and PUNCH4NFDI projects, which would allow http access to the lustre file server.

In addition, within EUROLABS, GSI supported by HGS-HIRe for FAIR hosted an Advanced Training School on Open Science and Data Management (Castle Ebernburg). The school brought together a diverse group of early-careers researchers, ranging from final year master's students to postdoctoral researchers. It aimed to develop skills and knowledge on Open Science principles, including Open data and software, workflows and tools. The lectures and hands-on sessions encouraged the participants to act as Open Science ambassadors for their research communities.

Research Data Management in Practice: An Example

It is now well established that generated research data at GSI/FAIR should adhere (as best as possible) to the F.A.I.R.-principles.

This means data should have a persistent identifier and be accompanied by the necessary software, computing resources, and documentation to enable reproducibility. However, providing full raw data and compute resources to everyone is not always practical or useful, so sharing processed or result data may be more appropriate in some cases.

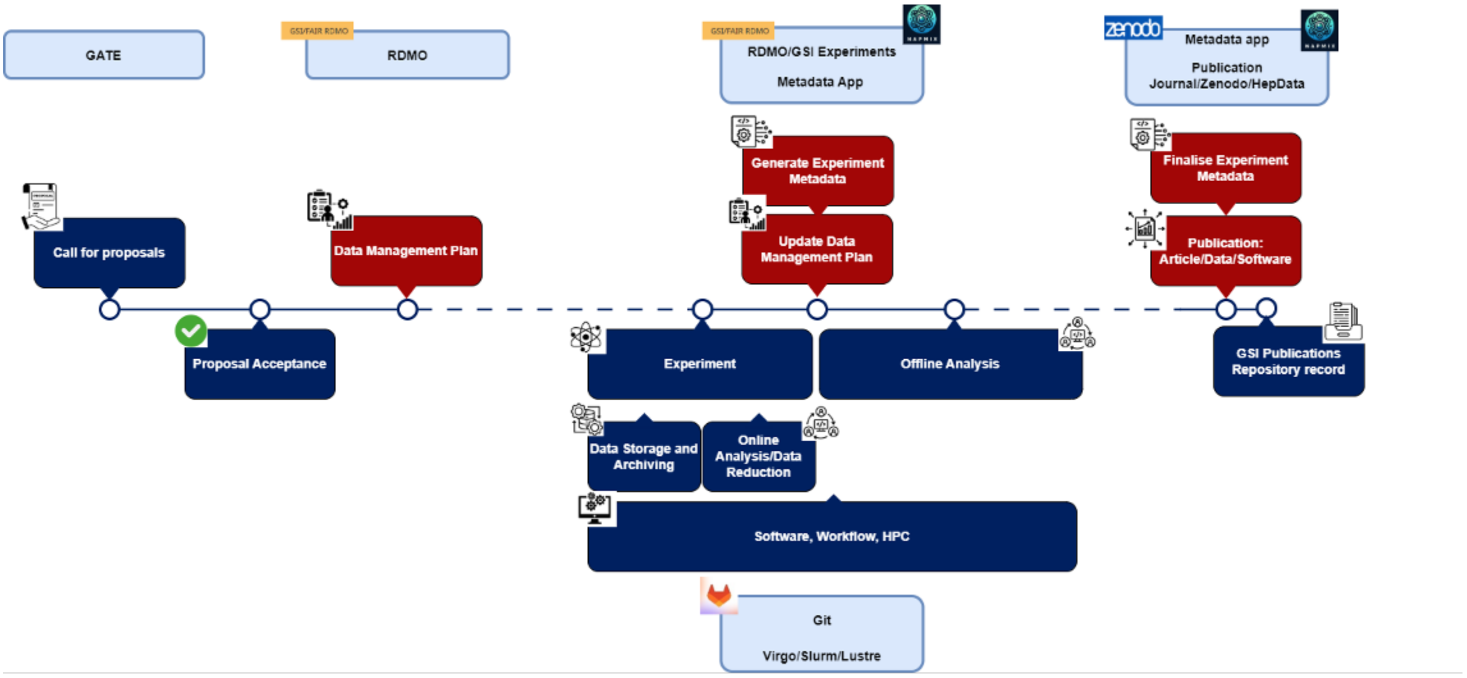


Figure 1: An example workflow for a research project at GSI

Figure 1 outlines a typical workflow for an experiment approved and run at GSI. The elements that are towards open science/RDM are indicated in red. These include the preparation of a data management plan, ensuring suitable metadata is included with a dataset, and ensuring that (where possible) the data and software is released at the time of journal article publication.

The RDM guidelines address the selection of appropriate data publication repositories, and instructions are available to encourage researchers to start the data publication process.

Irrespective of the location of the accessible data, it remains important that a record of the data be generated in the GSI publications repository in a similar fashion to the publication of a journal article.

2. Research of the APPA Departments

Coordination: Prof. Dr. Thomas Stöhlker (Helmholz 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 organized 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. 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 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 2 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 2 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 BMBF 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.

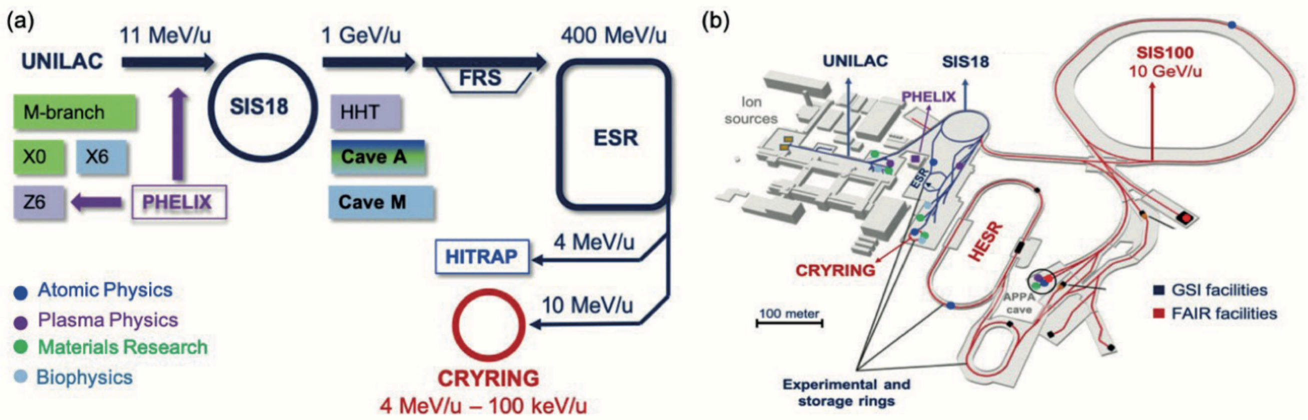


Figure 2: (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red) [1]

[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 (Helmholz Institute Jena, Friedrich Schiller University Jena & GSI)

Authors: Carsten Brandau (GSI), Alexandre Gumberidze (GSI), Robert Grisenti (GSI), Yuri Litvinov (GSI), Pierre-Michel Hillenbrand (GSI), Wolfgang Quint (GSI), Danyal Winters (GSI), Thomas Stöhlker (GSI & HI Jena)

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 working groups of the Department for Atomic, Quantum, and Fundamental Physics (AQF) 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 modularized FAIR facility) offers fascinating, worldwide unique possibilities by providing cooled heavy ion beams, for basically all elements (from hydrogen to uranium) in every charge state up to fully ionized uranium. A particular unique 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 allow for 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 neighboring fields such as accelerator physics, materials research, plasma physics, and especially atomic and nuclear astrophysics. To reach its research goals, particular important activities of the AP division are related to the development and implementation of novel, state of the art instrumentation (such as e.g., internal targets, lasers, X- and γ-ray polarimeters, cryogenic micro-calorimetric detectors for soft and hard X-rays, and Schottky devices). Instrumentation and detection concepts are permanently under scrutiny and in case adjusted, to enabled optimal use of the above-mentioned research infrastructures.

In 2024, several beam times have been successfully carried out at ESR and CRYRING@ESR facilities within the FAIR Phase-0 program. This also included installation and commissioning of new setups developed within the SPARC collaboration. In addition, a significant progress has been achieved in commissioning of the HITRAP facility towards a full user operation.

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 2024

Long-sought measurement of exotic beta decay in thallium helps extract the timescale of the Sun’s birth

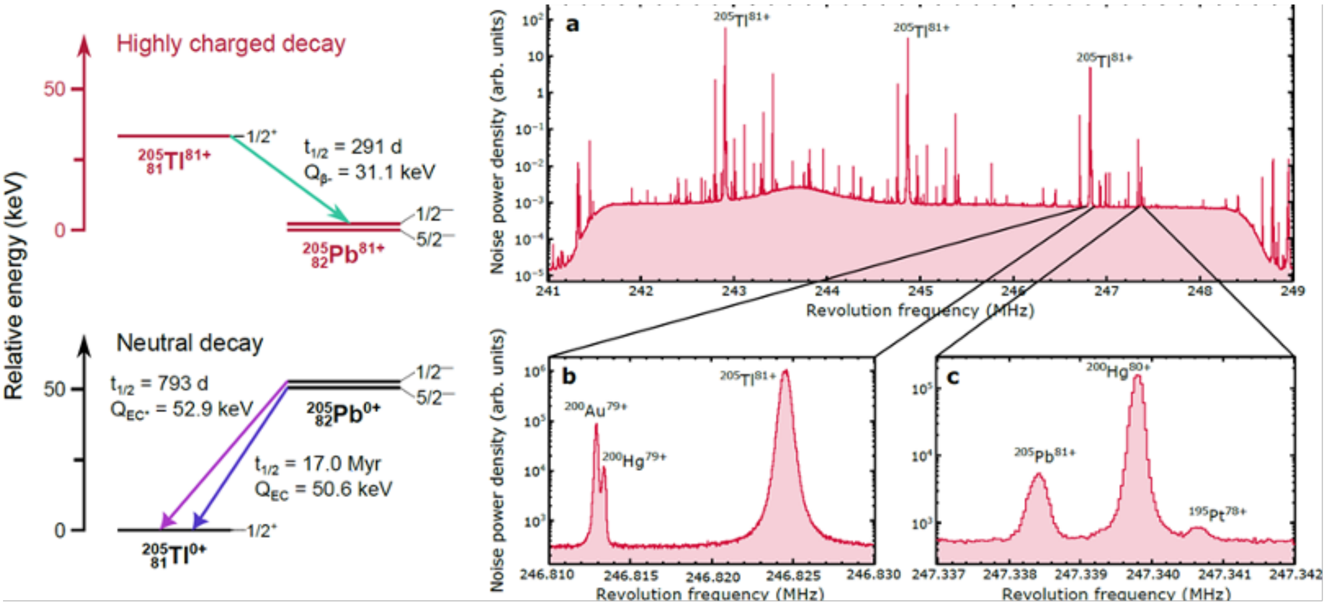


Figure 3: Decay scheme of neutral ^{205}Pb in comparison to bare ^{205}Tl^{81+}, along with recorded Schottky spectra where both the mother nuclei ^{205}Tl^{81+} as well as the daughter nuclei 205Pb81+ are clearly visible.

Specific electronic configurations in highly-charged ions can dramatically alter nuclear decay properties known in neutral atoms, whereby dominant decay channels can become disabled while new ones can open up. To model complex processes ongoing in extreme astrophysical environments, the detailed understanding of nuclear decays of highly charged ions is indispensable. Atomic ^{205}Tl is stable but becomes radioactive if fully striped off bound electrons (see Figure 3). The new channel, bound-state beta decay (β_b), is responsible for the large change of the half-life from stable to about one year. The rate of β_b(^{205}Tl^{81+}) is key to determine the cosmochemical origin of the solar system. In addition, ^{205}Tl^{81+}with its lowest known energy threshold for capturing electron neutrinos, is considered as a detector for solar pp neutrinos. The measurement of β_b(^{205}Tl^{81+}) has been proposed more than 40 years ago as a main motivation for the construction of the SIS18-FRS-ESR facilities at GSI. Successful accomplishment of the experiment was finally possible in 2021 at the SIS18-FRS-ESR complex which is currently the only facility worldwide where this measurement is feasible. Here, the radioactive nuclides can be prepared as highly charged ions and stored for extended time periods. The obtained decay rate is much smaller than predicted [1], severely constraining the usage of ^{205}Tl as neutrino detector. Extensive astrophysical calculations have convincingly shown that no peculiar stellar source contributed to composition of our solar system [2].

Deviation in the lifetime – First observation of the nuclear two-photon decay in bare atomic nuclei

For the first time, an international research team, led by GSI/FAIR scientists, the Institut de Recherche sur les Lois Fondamentales de l'Univers (IRFU) in Saclay, France, and the Max Planck Institute for Nuclear Physics in Heidelberg (MPIK) has succeeded in observing a two-photon decay in an atomic nucleus from which the entire electron shell has been removed.

Nuclear two-photon or double-gamma nuclear decay is an electromagnetic process in which a nucleus in an excited state emits two gamma rays simultaneously. This new type of decay was first discovered in the 1980s at the MPIK, but further investigations were hardly possible due to its rare nature. Studying this process gives insight into fundamental properties of the nucleus, such as the reaction to electromagnetic fields in different states of excitation.

In the recent experiments, this rare phenomenon was studied in a specific isotope of germanium, with mass number A=72, which was stripped of its entire electron shell [3]. For this purpose, a beam of krypton ions was accelerated to about 70% of the speed of light and subsequently passed through a beryllium plate with a thickness of one centimeter. In the collision, the required germanium ions are produced in a specific excited state, which has the same spin-parity quantum number 0^+ as the ground state, together with other ^{72}Ge isotopes in their ground state and other nuclei.

To force the same ion species to have identical revolution frequencies, the experimental storage ring ESR at GSI/FAIR was set into a special 'isochronous' mode, such that the differences in velocities are exactly compensated by the lengths of ion trajectories. As a result, the ground and the isomeric state of ^{72}Ge ions were separated despite their very tiny relative mass difference of the order of 10^{-6}.

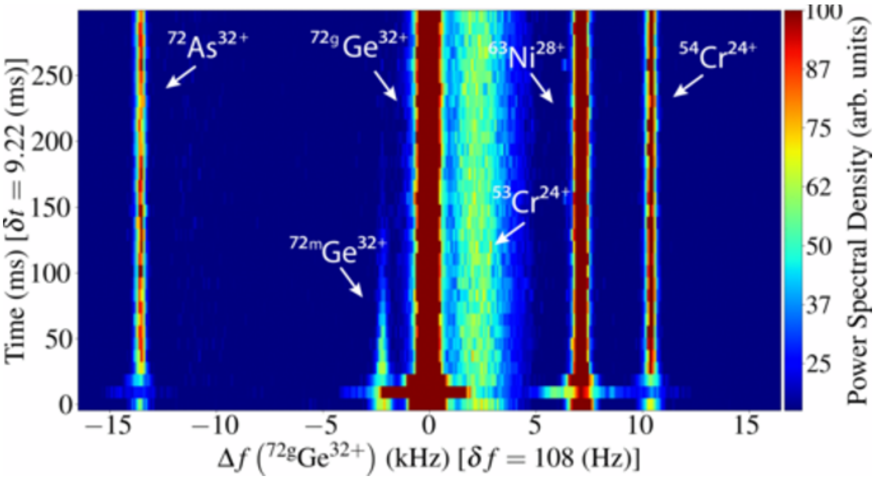


Figure 4: Time after injection (δt=9.22 ms per time bin) versus revolution frequency (δf=108 Hz per frequency bin) spectrogram of the sum of 102 single injections (setting 1) centered on ^{72g}Ge^{32+} from 0 to 300 ms. The power spectral density of each ion species is proportional to their ion number.

Each ion in the isomeric state was tracked non-destructively (see Figure 4) and the time of its decay was precisely determined. Thus, the half-life for the double-gamma decay of the first excited 0^+ state in bare germanium-72 ions was determined to be 23.9(6) milliseconds, which is fifty thousand times longer than in the atomic state and strongly deviates from theoretical expectations. The measured half-life is by at least two orders of magnitude shorter than the shortest lifetime directly measured previously for stored highly-charged ions.

Crystal Nucleation in Supercooled Atomic Liquids

In general, freezing of a liquid starts with the chance of formation of a crystalline seed made up of a small number of molecules. The century-old theory describing this crystal nucleation process has been, however, very difficult to test. Recently, our research team used liquid jets to provide the most stringent limits to date on the accuracy of the classical theory for two particularly simple liquids — krypton and argon [4]. Because in noble gases the atoms interact through simple Lennard-Jones potentials, the theory should be in a position to make accurate predictions. At the EU-XFEL, our jets were probed with X-ray pulses, allowing a measurement of the rate of crystal formation with exquisite accuracy (see Figure 5). For both liquids, the theory predicted a nucleation rate 100–1000 times higher than the experimental value. These results therefore offer the possibility to test non-classical extensions of the theory, thereby improving our knowledge of this critically important phase transition.

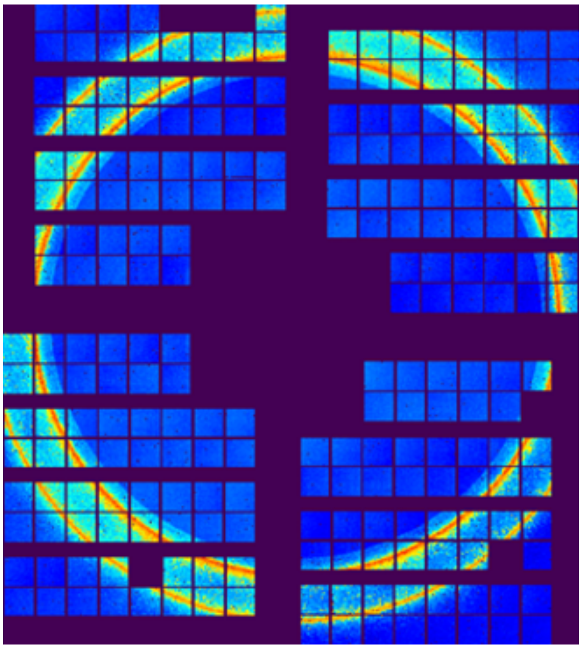


Figure 5: A diffraction pattern from 105 single-pulse X-ray exposures of the krypton jet soon after the onset of crystal nucleation, showing rings from specific crystal planes.

FAIR Phase-0: experiments

Cave A

Resonant coherent excitation at Cave A

After a few years of interruptions due to the pandemic limitations and the ESR upgrade activities, the precision spectroscopy experiments based on ion-crystal interaction, designed for APPA cave, have been restarted in FAIR Phase-0 at Cave A using extracted, cooled ESR beam. The setup, in large part provided by Japan with a GSI contribution to SPARC was improved. The large gain for this type of experiment consists of two aspects: the new accelerator control system installed at the GSI capability, which dramatically reduced the time needed for the beam transport from ESR to Cave A, and the new high voltage divider at the ESR cooler, with a 10^{-6}precision provided by TU Darmstadt. The data are currently being analyzed, but a first, preliminary evaluation shows already a significant improvement in the precision of the transition energy determination, as expected.

Considering the new project staging (APPA cave realization belongs to the FS++ stage), this kind of experiment should continue with the GSI beam at Cave A.

CRYRING@ESR

SPARC transverse free-electron target

This setup was built at the University of Giessen and funded by BMBF throughout its last funding periods, with the last share of core invest being granted within the current funding period. In May 2024, in-ring commissioning with a Ne^{7+} ion beam from the CRYRING local injector commenced (see Figure 6). During these initial experiments we could show that a) the ion beam could be injected into CRYRING with the target in place, b) neither electron beam nor ion beam show significant mutual interference, c) a low energy dense electron-beam could be generated that was not significantly influenced by the close-by ring dipole magnets, and d) the operation of the target did not severely compromise the ring-vacuum conditions. Based on these promising first results, it is planned to continue the commissioning in 2025 with a beam of highly charged ions injected into CRYRING via the synchrotron SIS/the storage ring ESR to demonstrate the feasibility of X-ray-spectroscopy experiments in free-electron-ion collisions at the electron target.

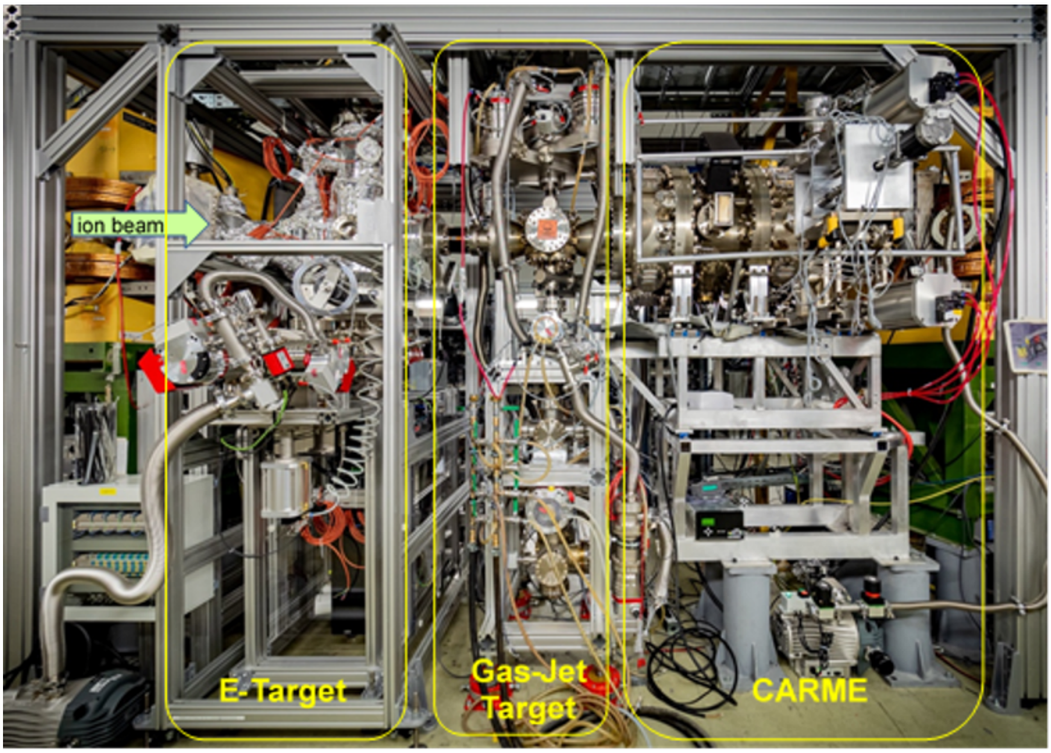


Figure 6: Experimental installations in the CRYRING section YR09. From left to right: electron target, gas-jet-target and the nuclear astrophysics detector array CARME.

Gas-jet target at CRYRING

The operation of the gas-jet target with H_2 was established and the requirements with respect to H_2 safety were implemented in a beam time with the CARME detector array in June 2024. This was a requirement for completing its Final Acceptance Test. During a subsequent beam time with a VUV spectrometer, the target was operated for the first time with the heavier target gases Krypton and Xenon. Since the commissioning of the new internal target station at CRYRING the full range of operational target gases could be thus demonstrated in the course of numerous experiments, namely Hydrogen, Nitrogen, Helium, Krypton and Xenon. This year, additional ongoing optimization efforts took place, e.g. the redesign of the fore vacuum system and the implementation of a fourth differential pumping stage in the target bump. These efforts aim towards a continuous further improvement in the overall reliability, versatility and handling of the target station over the coming experimental campaigns.

CARME detector array at CRYRING

The CARME charged particle detection array was funded by the Science and Technology Facilities Council of UK and constructed at the University of Edinburgh [5]. In June, experiments with a deuteron beam (G22-00200) to investigate a reaction relevant for Big Bang Nucleosynthesis and a $^{15}N^{1+/5+}$ beam (G22-00201) to investigate electron screening effects in low energy resonant reactions were conducted using the new hydrogen target and the CARME array. Significant knowledge of beam on target operation for nuclear reaction studies at the CRYRING was gathered and commissioning of the hydrogen target was successful. The full scientific aims of these measurements were not able to be achieved primarily due to insufficient target densities and uncertainties in the energy of the CRYRING beam. Data analysis is currently ongoing and the implementation of improvements for future experimental campaigns is underway.

Towards First Experiments at HITRAP

HITRAP Decelerator

For the HITRAP decelerator, multiple systems were modernized: a FESA solution for retractable detectors and electrostatic elements for the GTR5 section was adapted from CRYRING; a new FPGA-based timing system was developed for the trap; new power supplies optimized for low inductance were specified and ordered for the GTR3 magnets; the permanent magnet of the GTR4 detector was repaired and reinstalled, etc. The RF of IH system proved to be stable only up to a power of about 120 kW - sufficient for commissioning beams, but not for the upcoming experiments. Moreover, the beam time showed the need for a new IH triplet due to a water leak. Nevertheless, the facility was able to demonstrate ion deceleration and trapping for the first time (see Figure 7). Further activity was concentrated on the analysis of the ion cooling process, by implementing a mass separation system, detector development and realigning the GTR6-GTR7 beamline sections for a symmetric ion transport, as well as further expansion of the FAIR CS.

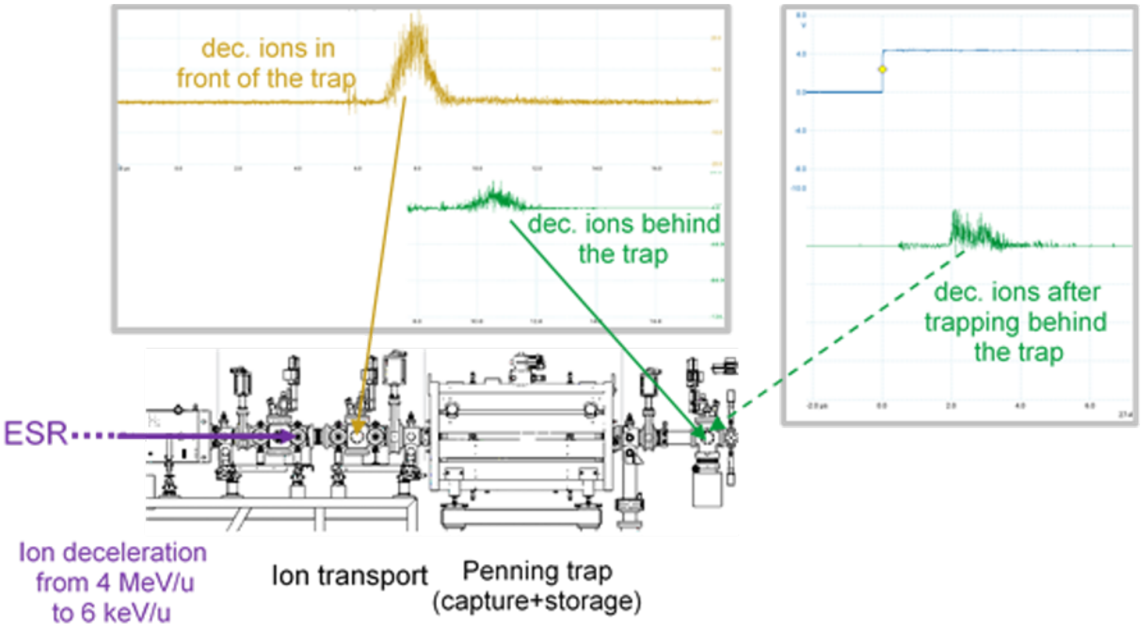


Figure 7: The HITRAP decelerator facility along with the signals from the decelerate ions at various stages.

SIS100

Laser cooling at SIS100

The groups at TU Darmstadt and TU Dresden have received the full FAIR core invest to build the laser systems for laser cooling at the SIS100. A novel concept will be used, where laser beams from three complementary laser systems (cw and pulsed) will be overlapped in space, time and frequency to interact simultaneously with a very broad ion velocity range in order to maximize the cooling efficiency. There will be two powerful pulsed laser systems with MHz repetition rates and variable pulse duration (10-100 ps and 50-740 ps) and one powerful tunable cw laser system. The picosecond laser pulses are broad in frequency and will enable fast cooling of injected ion beams with a large initial longitudinal momentum spread. The cw laser can be quickly tuned over a large range and has high spectral power, forcing the ion beams to remain cold during storage. This combination of 3 UV laser beams should be up for the challenge of suppressing intra-beam scattering and space charge effects.

The design of the second part of the SIS100 laser beam line, connecting the laser lab (located in the “maintenance tunnel”) to the SIS100 itself (located in the “accelerator tunnel”), was completed and after the design review approval, the procurement and manufacturing of components will now start. The installation of this part of the laser beam line is planned for spring 2025. Also, the laser lab for the SIS100 has been designed and planned. The lab construction is most-likely going to start in 2026.

Selected publications of 2024

[1] R. S. Sidhu *et al.*, “Bound-state beta decay of $^{205}\mathrm{Tl}^{81+}$ ions and the LOREX project,” *Phys. Rev. Lett.*, vol. 133, p. 232701, Dec. 2024, doi: 10.1103/PhysRevLett.133.232701.

[2] G. Leckenby *et al.*, “High-temperature 205Tl decay clarifies 205Pb dating in early solar system,” *Nature*, vol. 635, no. 8038, pp. 321–326, Nov. 2024, doi: 10.1038/s41586-024-08130-4.

[3] D. Freire-Fernández *et al.*, “Measurement of the isolated nuclear two-photon decay in $^{72}\mathrm{Ge}$,” *Phys. Rev. Lett.*, vol. 133, p. 022502, Jul. 2024, doi: 10.1103/PhysRevLett.133.022502.

[4] J. Möller *et al.*, “Crystal nucleation in supercooled atomic liquids,” *Phys. Rev. Lett.*, vol. 132, p. 206102, May 2024, doi: 10.1103/PhysRevLett.132.206102.

[5] J. J. Marsh *et al.*, “The first in-beam reaction measurement at CRYRING@ESR using the CARME array,” *Eur. Phys. J.* A, vol. 60, no. 4, p. 95, 2024, doi: 10.1140/epja/s10050-024-01318-2.

2.3 Materials research

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

Introduction

Authors: Mohan Li (GSI), Marilena Tomut (GSI & University of Münster), Christina Trautmann (GSI), Maik Lang (University of Tennessee), G. Wilde (University of Münster) and María Eugenia Toimil-Molares (GSI & TU Darmstadt)

The Materials Research activities encompass a broad range of projects involving ion-track nanotechnology and the interaction of swift heavy ions and solid state matter. Specific topics explored during last year include:

- ***Ion-track etched nanochannels and nanowires***: Tailored membranes with single- or multi-channels were developed for sensor applications. Additionally, size-dependent properties of electrodeposited three-dimensional nanowire networks were investigated. The specific aim is to develop metal nanowire networks for catalytic, thermoelectric and energy applications.
- ***Material modification induced by heavy ions****:* Radiation damage was analyzed in a variety of bulk and nano materials ranging from carbon-based materials (both classic and new carbon forms) to ceramics, high-entropy alloys, functional materials, actinide targets for superheavy element production and nanowires.
- ***Materials under multiple extreme conditions****:* The response of materials under multiple extreme conditions is of great interest for the synthesis of new materials and for geosciences to simulate processes in the Earth's mantle. High pressure, high temperature, and high radiation doses (or any combination thereof) induce significant changes in the atomic and electronic structure of many materials. The heavy-ion beams delivered by the SIS18 accelerator (and in the future by SIS100) can penetrate through several mm of a diamond anvil cell (DAC). The enormous amount of energy deposited by the ions in the pressurized sample drives the system out of equilibrium. The combination of ion irradiation and high static pressure can trigger and stabilize unique structural changes, which are not produced by ions or high pressure alone.

To support the interdisciplinary MAT collaboration, which consists of more than 40 groups from Germany and abroad, the Materials Research Department maintains and operates several beamlines with an extensive variety of in-situ analysis techniques: X0 and M-branch (at the UNILAC), Cave A (at SIS-18) and the new Mat-Station at the CRYRING.

Highlights in 2024

Atomic-scale structure of ZrO_2: Understanding the formation of metastable polymorphs by GeV ion irradiation

Synthesizing the tetragonal metastable high-temperature phase of zirconia (ZrO_2) is of significant interest in materials science because it offers remarkable properties including high strength and excellent electrical conductivity. Besides doping or reducing the grain size, one possibility to stabilize this phase at ambient temperature while maintaining its superior properties, is ion irradiation. In all cases structural defects are utilized to force a material to maintain a structure that is normally unstable under ambient conditions. In a recent study [1], the well-known metastable tetragonal ZrO_2 phase was stabilized by irradiating monoclinic zirconia with 1.47 GeV Au ions to a fluence of 10^{13} ions/cm^2. Structural analysis by neutron total scattering revealed a large degree of structural complexity and heterogeneity with the presence of an underlying orthorhombic nanodomain structure, which was further confirmed by X-ray absorption spectroscopy. Simulating the experimental neutron scattering data, using a supercell of four 2-nm orthorhombic domains, accurately captures the structural transition from short-range orthorhombic (intra-domain) correlations to long-range tetragonal (inter-domain) correlations. This confirms that metastable zirconia consists of nanoscale orthorhombic domains, which yield the tetragonal long-range structure by ensemble averaging. This is in clear contrast with the equilibrium picture of a tetragonal high-temperature phase that is homogeneous across all structural length scales. Interestingly, the orthorhombic nanoscale phase is not part of the equilibrium phase diagram and was predicted based on simulations as transient saddle-point phase but had not been experimentally confirmed until now (see Figure 8). These findings were only made possible by the ability to produce sufficient quantities of irradiated materials at the UNILAC beamline X0 using swift heavy ions coupled with neutron scattering experiments at the world's most intense spallation neutron source at Oak Ridge National Laboratory.

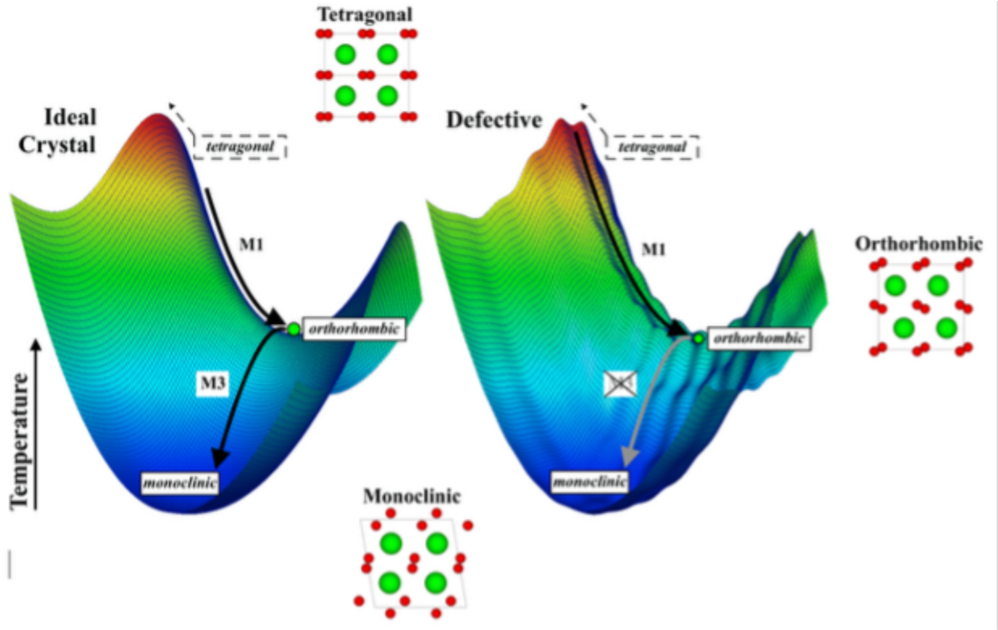


Figure 8: Qualitative energy landscape of two-step phase transition pathway (M1 & M3 phonons) between tetragonal (P4$_2$/nmc) and monoclinic (P2$_1$/c) ZrO$_2$ phases. Defects stabilize an intermediate transient orthorhombic (Pbcn) polymorph at Landau free energy saddle point. Adapted from Ref. [1]

Three-dimensional gold nanowire networks with tailorable surface wetting states: from Rose-Petal Effect to Super-Hydrophilicity

Wetting phenomena on solid surfaces, particularly when considering nanostructured surfaces, display intriguing and complex interactions with different kinds of liquids, captivating the attention of researchers in various scientific fields. It is known that the wetting state of a surface is impacted by characteristics such as surface-area-to-volume ratio, surface roughness, the presence of nanostructures, as well as the surface chemical composition. With proper designs, synthetic structures can mimic hydrophobic behaviors in Nature, such as those displayed by lotus leaves or insect wings, which effectively repel water. Surface characteristics can also enhance the surface wettability, such as hierarchical surface patterns for applications like microfluidic devices, where precise control of liquid flow is critical.

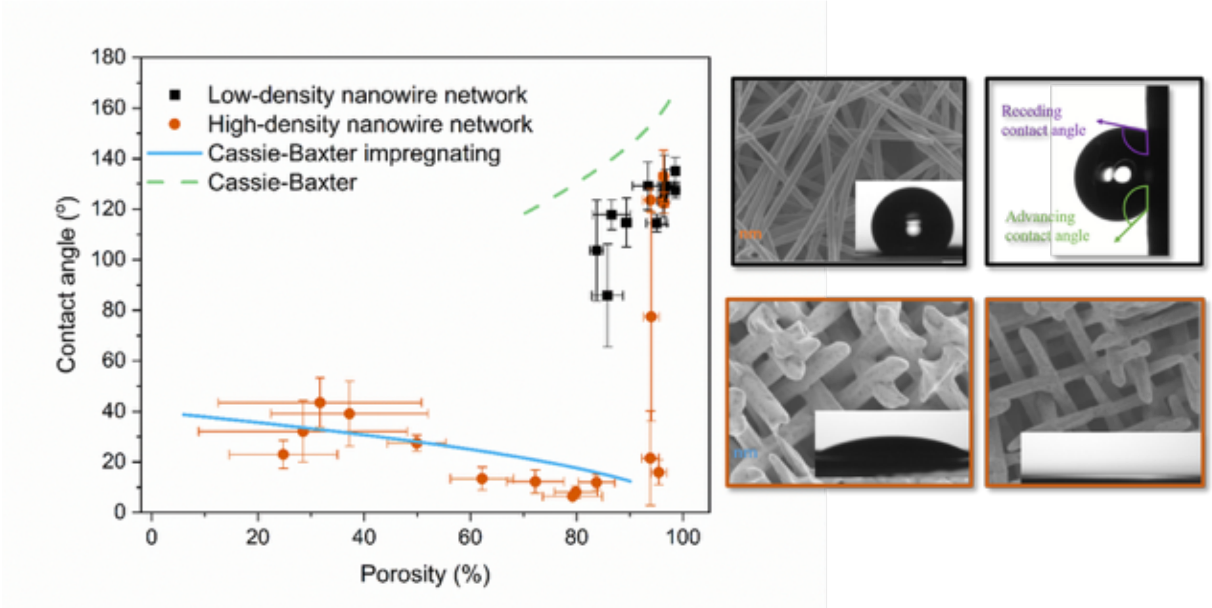


Figure 9: (Left) Measured contact angle values versus the nanowire network porosity visualizing the influence of the network porosity on wetting state transition. The corresponding values estimated with the models of Cassie-Baxter (solid blue line) and Cassie-Baxter impregnating (dash green line) are also shown. (Right) Scanning electron microscopy images of representative nanowire networks and photos of the sessile drop on the sample surface. Adapted from Ref. [2].

We have demonstrated that the wettability of tailored 3D porous freestanding gold nanowire networks created by the gold electrodeposition in etched ion-track templates can be tailored by controlling its porosity. Gold was selected for this study, due to its chemical stability. Despite the hydrophilic nature of bulk gold, the developed porous structures exhibit various wetting states depending on their geometry. Thanks to a systematic and independent variation of nanowire density and diameter, we could show that the NWNWs with low-porosity (< 60%) exhibit hydrophilicity (CA = 20° - 50°), while the medium-porosity samples from 60% to 80% exhibit super-hydrophilicity (CA < 10°), the hemi-wicking effect playing a major role. The NWNWs with porosity higher than 95% exhibit instead very high contact angles (120° - 130°) and high adhesion of water droplets to the sample surface, which revealed three major aspects of the rose-petal effect: high contact angle, high adhesion, and high contact angle hysteresis.

Tayloring mechanical properties of bulk metallic glasses using swift heavy ions irradiation

Bulk Metallic Glasses (BMGs) are amorphous alloys known for their exceptional mechanical strength, high elastic limits, and corrosion resistance. However, their practical use is often limited by their intrinsic brittleness, arising from highly localized shear banding and the absence of strain hardening mechanisms. Traditional approaches to improving ductility, such as alloy design or in situ composite formation, offer limited tunability and scalability. We explored a novel, non-equilibrium method for modifying the mechanical behavior of BMGs using swift heavy ion (SHI) irradiation. Unlike atomic collisions damage processes, SHI deposit energy primarily via electronic excitations, resulting in localized, high-temperature transient regions (thermal spikes) without long-range ballistic displacement. These interactions can induce rearrangements at the nanoscale, free volume redistribution, and in some cases, partial nano-crystallization — all of which may influence the initiation and propagation of shear bands. Advanced characterization techniques (transmission electron microscopy, nanoindentation and differential scanning calorimetry) revealed that these changes are closely linked to ion-induced localized rejuvenation-relaxation effects leading to structural heterogeneity [3]. Creation of ion tracks with enhanced excess volume and medium range order, influence the nucleation and propagation of shear bands in irradiated bulk metallic glasses. This leads to a change of the deformation mechanism from shear band dominated to plastic flow, as shown in Figure 10, improving the ductility and opening new application perspectives of these novel materials.

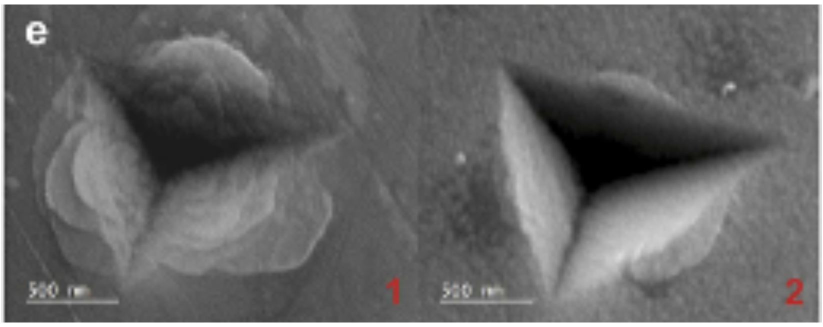


Figure 10: SEM images of indents on $Pd_{40}Ni_{40}P_{20}$ bulk metallic glass: Left: non-irradiated; right: exposed to Au ions with a fluence of $5x10^{12}$ i/cm^2. The pristine material clearly shows several shear bands created under the tip of the nanoindenter that reach the surface of the sample around the indent. In contrast, almost no shear bends can be observed around the indent in the irradiated BMG

Outlook 2025

Following the ‘Call for Proposals’ for beamtime in 2024 and 2025, the MAT-PAC evaluated the scientific excellence and recommended 19 A-rated proposals as high priority experiments. For the next beamtime block in early 2025, FAIR Phase-0 activities will continue at all MAT-operated beamlines. The department activities in two new cross-center Helmholtz Innovation pool projects, MATHIPE (Materials under High Pressure) and FISVIR (The use of large research infrastructures (RIs) in the fight against virus-based diseases), as well as in the highly interdisciplinary IVF project CORAERO will be continued. Within a new third-party funding project, DINERWA, which will run from 2025 until 2028, we will start in 2025, we will start novel investigations of the radiation hardness of fusion materials (W and HEA nanostructured materials and ODS steel) using in-situ analysis during ion irradiation.

Selected publications of 2024

[1] A. P. Solomon *et al.*, “Atomic-scale structure of ZrO2: Formation of metastable polymorphs,” *Science Advances*, vol. 11, no. 1, p. eadq5943, 2025, doi: 10.1126/sciadv.adq5943

[2] M. Li *et al.*, "3D Gold Nanowire Networks with Tailorable Surface Wetting State: From Rose-Petal Effect to Super-Hydrophilicity," *Small* (2025) 2411971, 1-8, doi: 10.1002/smll.202411971

[3] S. Khademorezaian *et al.*, "Extreme rejuvenation of a bulk metallic glass at the nanoscale by swift heavy ion irradiation," *J. of Alloys and Compounds* 980 (2024), 173571, doi: 10.1016/j.jallcom.2024.173571

2.4 Plasma physics

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

Introduction

Authors: P. Neumayer, A. Blazevic, S. Götte, M. Metternich, O. Rosmej (GSI), V. Bagnoud (GSI, HI Jena & TU Darmstadt), J. Cikhardt (CTU Prague), G. Gregori (University of Oxford)

The study of high energy density (HED) plasmas at high pressures (Mbar) and temperatures (eV to keV) is relevant for understanding astrophysical objects such as planets and stars, for the interaction of (ultra-) intense laser pulses with matter, or for the goal of achieving thermonuclear fusion by inertial confinement. Powerful drivers such as large laser facilities and accelerators make it possible to create such extreme states of matter 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 facility PHELIX allows precise measurements of the ion stopping power in laser-generated hot plasmas as well as to investigate advantages of combining laser-accelerated ions and conventional accelerator structures. 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 SIS18 synchrotron, heavy ion pulses with $>10^9$ ions per bunch can be focused to millimeter spot sizes and compressed to sub-μs duration, allowing macroscopic samples to be volumetrically heated to extreme conditions. 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 FAIR-relevant 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

In 2024, a total of eight experiments were performed using the PHELIX laser facility. Of these, four took place in the PHELIX target area as laser-only experiments. At the HHT cave one beamtime combining laser pulses with heavy-ion beams from the SIS18 was conducted. In addition, a preparatory beamtime for future LPI studies was also carried out at HHT. Finally, a double experiment was performed at the Z6 area, continuing the series of LIGHT, in which laser-accelerated ions are combined with conventional accelerator components. A total of 522 experimental shots were registered in the PHELIX shot database, of which only seven (just over one percent) were marked as failure. This may serve as a measure that PHELIX does not work with a high cadence, but relatively reliably.

As can be seen in Figure 11, nearly half of the time in 2024, as in previous years, was spent on preparing and conducting the experiments. The largest single item is the time spent on maintenance, which - as in previous years - accounted for 46%. PHELIX has been in operation since 2008, i.e. for 17 years now, and the effort required to keep the system operational is correspondingly high.

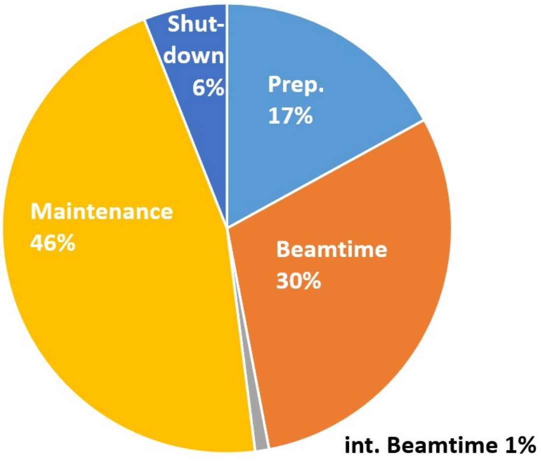


Figure 11: Statistics of PHELIX operation in 2024.

However, maintenance also included the time for conversions and upgrades as well as system tests [1]. As an example, a new a broadband front end was commissioned, providing up to 1% of bandwidth. Together with a new frequency doubling crystal installed in the HHT beamline at the beginning of 2025, this will enable experiments investigating novel strategies to mitigate laser-plasma instabilities (LPI) in the context of laser inertial fusion. As part of the European THRILL (Technology for High-Repetition-Rate Intense Laser Laboratories) project, an actively cooled Nd glass slab amplifier with a large (>30 cm) aperture is being developed. The goal is to overcome the thermal management challenges associated with high-energy, high-repetition-rate laser systems. Two critical aspects are emphasized: thermal isolation and active cooling of the gain medium and its surroundings. The custom-designed amplifier housing integrates flashlamps into a water-cooled enclosure, which significantly reduces recovery time from thermally induced long-term aberrations—from 90 minutes, as observed in nitrogen-purged systems like the GSI PHELIX laser, to just 5–10 minutes. However, this improvement comes at the cost of approximately 30% lower pumping efficiency. Nevertheless, the new design offers a promising approach to optimizing high-repetition-rate laser systems. Current efforts are directed toward enhancing the optical efficiency of the cooled prototype.

Highlights in 2024

At the Z6 experimental area, an experiment in the field of laboratory astrophysics was performed, exploiting the unique combination of high-energy laser pulses with ion beams from GSI's UNILAC. The goal was to investigate ion acceleration and diffusion in a laser-driven magnetized plasma, mechanisms that could provide an explanation for the origin of cosmic rays [2]. A mono-energetic beam of chromium ions with initial energies of 450.4 or 455.0 MeV was fired through a magnetized interaction region formed by the collision of two counter-propagating laser-ablated plasma jets, with resultant energy characteristics measured by a time-of-flight diagnostic. Plasma parameters were diagnosed with the use of laser interferometry, revealing the absence of strong fluid-scale turbulence. In spite of this, evidence of acceleration and diffusion consistent with a wave-particle interaction was found.

Microstructured materials and low-density foams are being considered for a variety of applications both in laser-matter interaction experiments and as components in targets for inertial confinement fusion. An important property, crucial for realistic modeling of such materials under intense laser irradiation, is the process of homogenization, i.e. the transition of the microstructure to a homogeneous plasma of the same average density. At PHELIX, an experiment visualizing this rapid homogenization was performed in the framework of a European IFE-project. The experiment used the two-pulse capability at PHELIX to produce both an intense pulse of laser-accelerated protons to volumetrically heat foam samples, and to generate a bright X-ray flash for imaging. A Talbot-interferometer [3] was employed, using the dark-field imaging mode to visualize structure well below the spatial resolution limit of the radiographic imaging setup (see Figure 12). These measurements demonstrate the viability of grating-based dark-field imaging for observing changes in foam microstructures, spatially resolved over large scale samples, and will allow to benchmark models describing the rapid homogenization process.

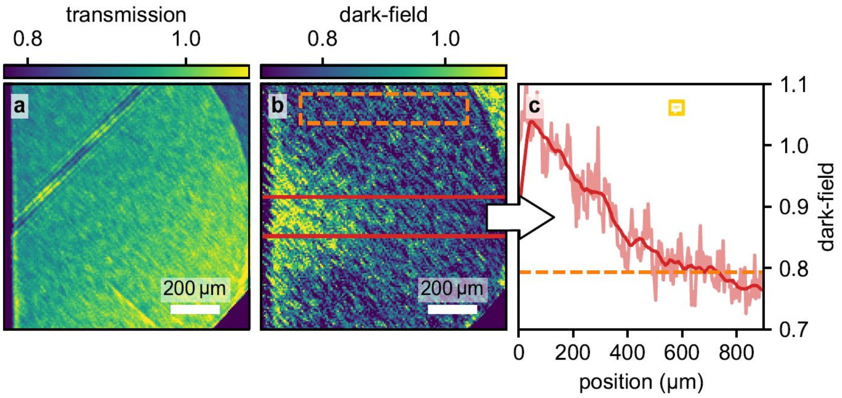


Figure 12: Dark field imaging.

In an approved beamtime at ARC/NIF, scheduled for early 2026, foam targets will be used for the first time. In preparation of this mission, the PHELIX laser was used as a testbed to investigate electron acceleration in pre-ionized foams at a large focal spot and near-relativistic laser intensity, laser parameters characteristic for the ARC beamline. At laser intensity of 10^{18} W/cm^2, a breakthrough in generating directed electron beams was achieved, with an effective temperature of up to 10 MeV, about 100 times higher than the temperature typically observed for laser shots at conventional foil targets. The combination of a foam layer with a high-Z converter enables the generation of gamma rays with energies up to 30 MeV and production of isotopes and neutrons due to photonuclear reactions.

Another experiment at the PHELIX target area was performed to study plasma expansion, electron acceleration, and electromagnetic pulse (EMP) emission. The sub-picosecond laser beam was split into a main beam for laser-target interaction and a backlighter beam for probing the expanding plasma via copper Kα radiation (8.04 keV). Electron emission from 1 µm thick aluminum foil targets was characterized using a set of magnetic spectrometers. Time-of-flight detectors revealed the presence of protons with energies exceeding 20 MeV at laser intensities on the order of 10^{19} W/cm^2. The escape of charged particles resulted in the formation of a strong, time-varying net charge, which in turn generated intense EMP. This EMP was characterized using differential B-dot probes placed in the near field inside the vacuum chamber, and horizontally and vertically polarized double-ridged horn antennas located outside the chamber. In both near-field and far-field measurements, the EMP spectrum exhibited strong components with frequencies significantly exceeding 10 GHz - well above typical EMP frequencies observed at similar laser facilities. The observed EMP appears to be driven predominantly by processes within the plasma and by the motion of charged particles in vacuum.

For experiments using intense heavy-ions pulses from the SIS18 synchrotron for volumetric heating, the high-energy laser beamline from PHELIX to the HHT-cave enables diagnostic techniques probing by powerful laser-driven x-ray sources. In the 2024 beamtime block, we have for the first time performed X-ray absorption spectroscopy to characterize samples heated by the heavy-ion beam [4]. Based on results from a previous laser-only beamtime to test and down-select different x-ray backlighter options as well as spectrometer setups, the combined experiment successfully recorded highly resolved absorption spectra around and above the aluminum K-edge from samples heated by the heavy-ion beam to well above the melt temperature. Figure 13 shows absorption spectra from samples heated to different temperatures by variation of the ion pulse intensity. The modulations above the K-edge can be attributed to interference effects of photo-electrons scattering from neighboring ions in the crystalline lattice of the sample material. Upon heating and melting, the crystalline order dissolves, leading to the modulations to disappear - a microscopic temperature diagnostic as well as a tell-tale sign for melting.

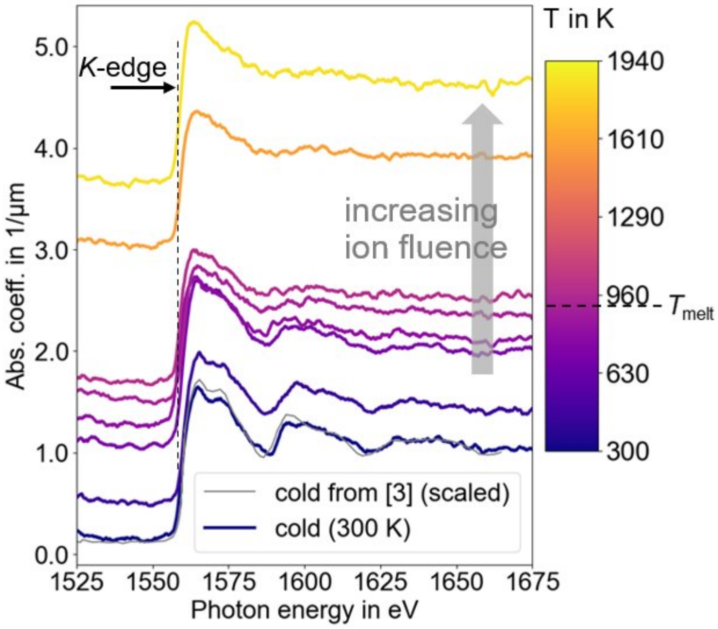


Figure 13: Absorption spectra from samples heated to different temperatures by varying the intensity of the ion pulse

Outlook 2025

After many years of operation, the PHELIX pulse compressor will be equipped with new large-scale compression gratings. This will allow to significantly increase the available laser energy for sub-picosecond pulses, the decisive parameter for reaching the highest energies in laser-ion acceleration.

In the field of laser inertial fusion, first experiments will be conducted at HHT to study Stimulated Raman Scattering and hot-electron generation in fusion-relevant plasmas, using the unique high-energy broadband capabilities of PHELIX.

Also at HHT, a confinement chamber will be installed and commissioned. This will allow in the future to generate Mbar pressures in macroscopic samples by the use of high explosives, which can be studied by the proton microscope PRIOR of FAIR [5].

Selected publications of 2024

[1] Zs. Major *et al.*, “High-energy laser facility PHELIX at GSI: Latest advances and extended capabilities,” *High Power Laser Science and Engineering*, vol. 12, p. e39, 2024, doi: 10.1017/hpl.2024.17.

[2] K. Moczulski *et al.*, “Numerical simulations of laser-driven experiments of ion acceleration in stochastic magnetic fields,” *Physics of Plasmas*, vol. 31, no. 12, p. 122105, Dec. 2024, doi: 10.1063/5.0223496.

[3] L. Wegert *et al.*, “Demonstrating grating-based phase-contrast imaging of laser-driven shock waves,” *Matter and Radiation at Extremes*, vol. 9, no. 4, p. 047803, Jun. 2024, doi: 10.1063/5.0200440.

[4] J. Lütgert *et al.*, “Temperature and structure measurements of heavy-ion-heated diamond using in situ x-ray diagnostics” *Matter and Radiation at Extremes*, vol. 9, no. 4, p. 047802, Jun. 2024, doi: 10.1063/5.0203005.

[5] M. Schanz *et al.*, “Design and commissioning of the PRIOR-II ‘proton microscope for FAIR’,” *Review of Scientific Instruments*, vol. 95, no. 12, p. 123704, Dec. 2024, doi: 10.1063/5.0220086.

2.5 Biophysics

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

Introduction

Authors: Prof. Dr. Marco Durante

The Biophysics Department (www.gsi.de/biophysik) 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 97 members with background in physics, biology, chemistry, and engineering. The Department is organized in 9 groups, 4 about physics and 5 about biology. Out of the 97 members, only 31 are staff, and we have 47% women and 37% foreign nationals from 16 different nationalities. The Department has pioneered heavy ion therapy in Europe and is currently focussing on research. 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 (IBC; www.gsi.de/bio-coll) 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 Super-FRS station (ring branch) and at the CBM cave. The initiative was approved by the FAIR Joint Scientific Council and the TDR for the setups are currently under evaluation at the Expert Committee Experiments (ECE). In 2024 we signed MoUs with both CBM and NUSTAR collaborations for the installations of Biophysics setup in the new caves. The first experiment on the ring branch has been proposed by members of the IBC [1] will focus on the biological properties of very exotic nuclei such as ^{8}He, whose β^{-} decay in ^{8}Li eventually leads to the production of two α particles (that enhance the biological effectiveness in the Bragg peak) and one γ-ray of 981 keV that can be used for online range identification. On the other hand, we plan to install the GSI galactic cosmic ray (GCR) simulator in the CBM cave, precisely on the platform that will eventually be the base of the HADES detector (Figure 14). With this setup, the GCR simulator will be able to reach a maximum energy of 10 GeV/n, an order of magnitude higher of the current setup installed in the GSI Cave A and of the only other GCR simulator in the world, used by NASA at the Brookhaven National Laboratory in the USA. This world-record GCR simulator will then be used by the ESA and IBC for testing of biological effects, shielding, and effects on the microelectronics with a realistic GCR spectrum.

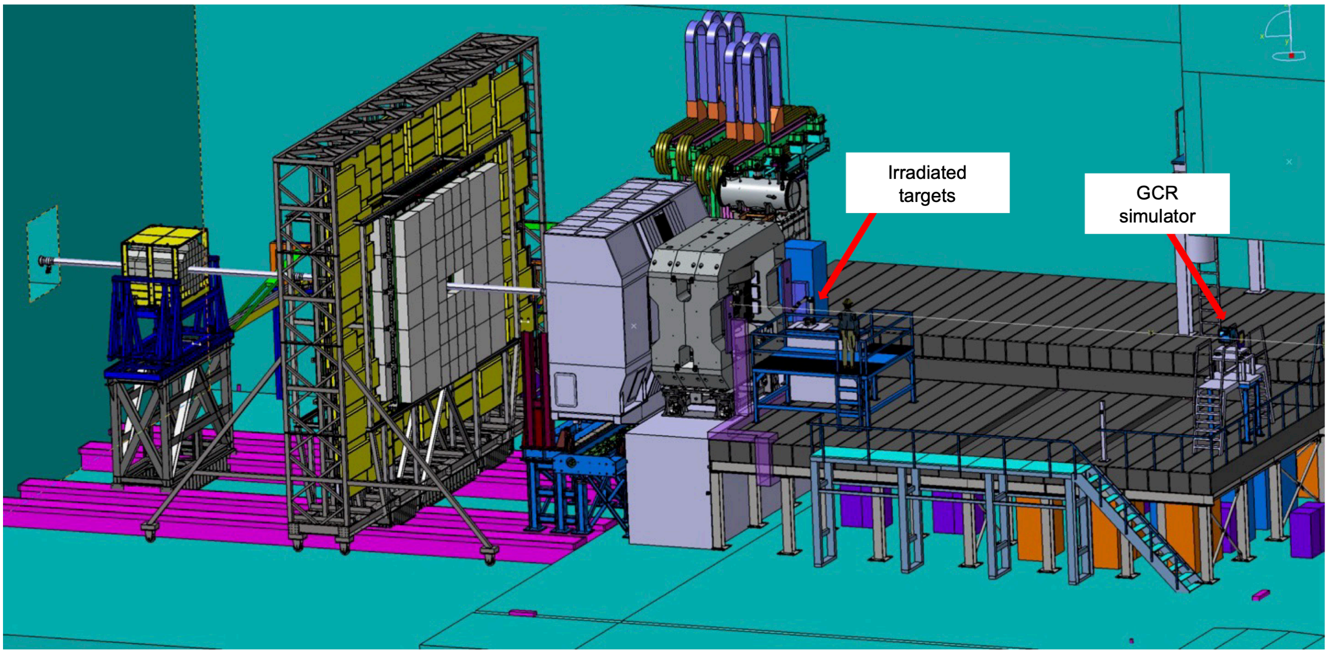
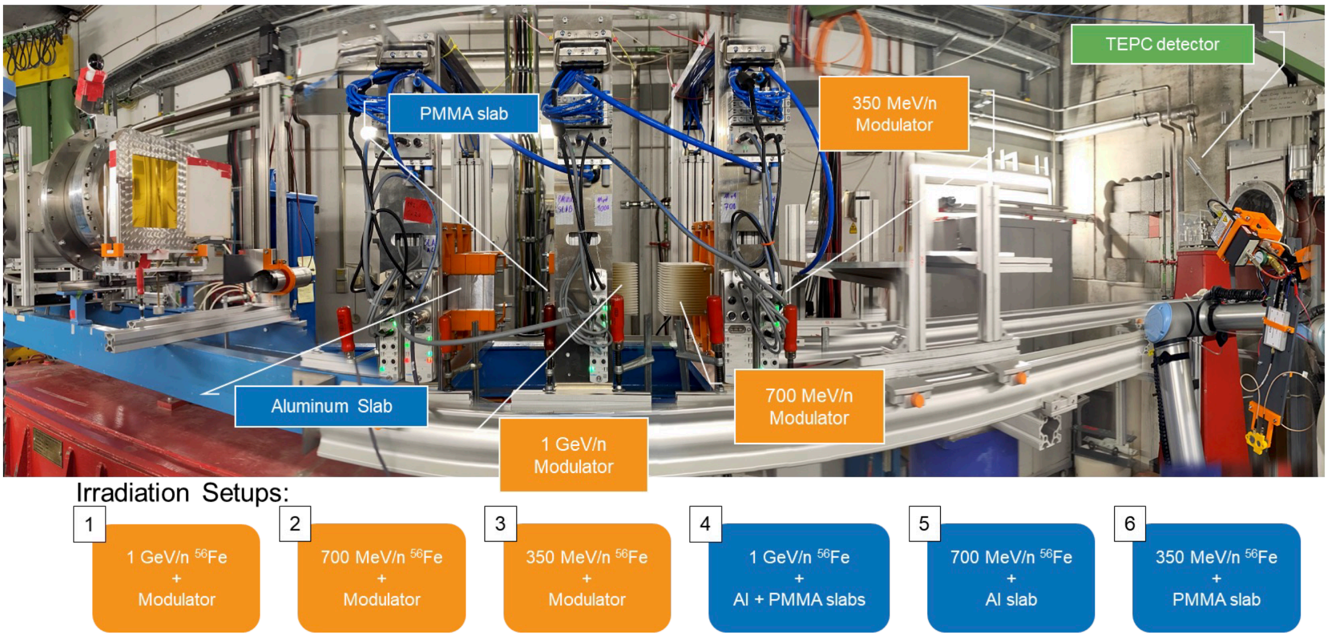


Figure 14: Graphical representation of the GCR simulator setup mounted in the future CBM cave. The CBM detector itself will be used in the initial phase to fully characterize the spectrum produced by the GCR simulator, which exploits a ^{56}Fe-ion beam impinging on different blocks to produce fragmentation spectra similar to the GCR composition and energy spectrum.

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; www.gsi.de/IBER). A large experimental campaign with ^{56}Fe-ions has been completed in 2024 to serve the experiments selected within the ESA-IBPER project. A highlight of the IBPER project has been the study of the radiosensitivity of the bdelloid rotifer *Adineta vaga* [2], a microscopic aquatic animal able to survive complete dehydration. The study, led by a Belgian group of the IBC, proved that the extreme resistance of bdelloid rotifers to radiation, including heavy ions, is a consequence of their capacity to resist complete desiccation. The beamtime was also used to complete the commissioning of the GCR simulator that will be fully operational for external user in the 2025 beamtime (Figure 15). Moreover, we organized the 4th edition of the ESA-FAIR Summer School (www.gsi.de/esa-fair-summer-school.htm) with 16 students from all over the world studying and working on space radiation protection at ESOC and GSI in Darmstadt.



Slide design courtesy of Luca Lunati

Figure 15: A photograph of the full GCR simulator setup commissioned in cave A during the 2024 beamtime. Image courtesy of Luca Lunati, GSI.

Awards

- Prof. Marco Durante received the Ellen Gleditsch award of the Norwegian Academy of Sciences for his outstanding contributions to radiation research. The award consists of a bronze statue representing Ellen Gleditsch, a student of Marie Curie and pioneer of radioactivity research in Norway, and a diploma. In addition, Prof. Durante gave an invited lecture to the members of the Academy of Sciences in Oslo.
- Amèlia Jansen van Vuuren won the first prize of the European Space Agency (ESA) for her work presented at the Annual Meeting of the European Radiation Research Society (ERRS).
- Maria Chiara Martire and Tamara Vitacchio received the “Giersch Excellence Award 2024” from the HGS-Hire Graduate School for their outstanding scientific work during their ongoing Ph.D.

Grants

The GSI Biophysics Department has successfully coordinated the large EU MSCA Doctoral Networks UPLIFT, aiming to expand the perspectives of tumor therapy with an innovative approach. The project is led by GSI scientists Prof. Christian Graeff and Dr. Lennart Volz. It brings together 15 leading scientific institutions and industrial partners from across Europe and is dedicated to developing the radiation therapy in an upright position — a paradigm shift that could significantly improve global access to advanced cancer treatments. The large network is funded with 4 M€ from EU plus 600 k€ from the Swiss State Secretary.

Highlights in 2024

This year was exceptionally productive for the Biophysics Department, with 36 peer-reviewed papers in the repository. A few highlights are provided below.

An agent-based model of lung fibrosis

Over half of all patients with lung cancer are treated using radiotherapy. Although this approach is effective, it leaves up to 30% of recipients with radiation-induced injuries. These can trigger serious conditions that affect breathing, such as fibrosis – in which the lining of the alveoli in the lungs is thickened and stiffened – and pneumonitis – when the walls of the alveoli become inflamed. Currently, radiotherapy fractionation schemes are chosen based on past experience and generalized statistical models to reduce the risk of fibrosis and pneumonitis, so are not optimized for individual patients. We developed a fully mechanistic model of radiation-induced fibrosis by combing an agent based-model (the BioDynaMo platform) of the pulmonary cells (Figure 16) with a Monte Carlo simulation of the radiation used for the treatment. The model reproduces the experimental data for the induction of fibrosis after both photon and proton irradiation [3]. The model gives an opportunity for a truly personalized approach to lung cancer radiotherapy, and is one of the first examples of really mechanistic model that goes from the primary radiation interaction up to a medical condition. For this very reason, the paper was selected by the Institute of Physics (IOP) as one of the "*Top 10 Breakthrough in Physics in 2024*" (https://physicsworld.com/a/top-10-breakthroughs-of-the-year-in-physics-for-2024-revealed/).

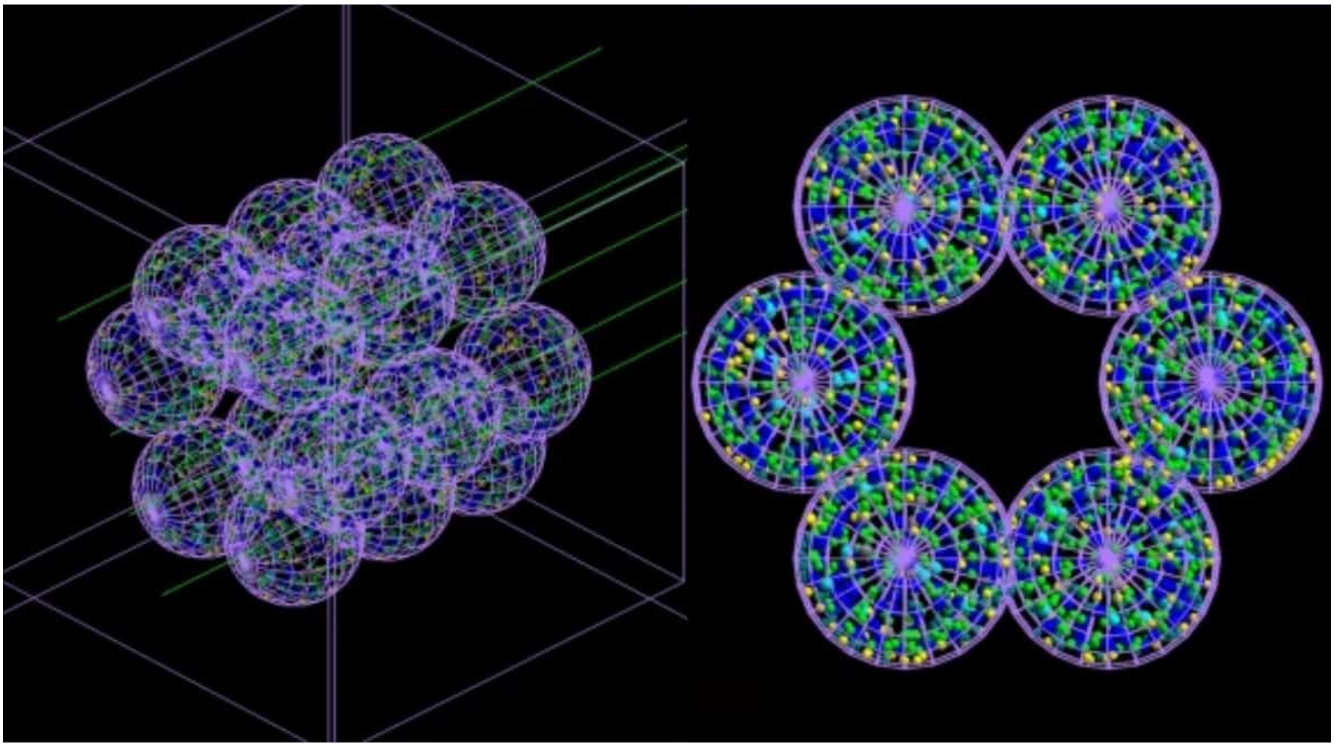


Figure 16: Computational model of alveolar tissue consisting of 18 alveoli. Images from ref. 3, reproduced under CC-BY 3.0 license.

mRNA vaccines and carbon ion radiotherapy

The recent introduction of immunotherapy has opened new avenues to fight advanced, metastatic cancers. While in most cases checkpoint inhibitors are used, a promising approach is to use mRNA vaccines. Well known for their use during the coronavirus pandemics, these vaccines can be used as personalized vaccines if the lipid carriers are loaded with the mutated mRNA of an individual cancer. Still local therapy is needed, and heavy ion therapy can be an ideal partner, given its high effectiveness in eliciting an immune response. For this reason, GSI has partnered with TRON (the research, non-profit branch of BIOTECH in Mainz) to study the combination of carbon ion irradiation and mRNA vaccine in a mouse model of colon adenocarcinoma. The results [4] showed excellent control of the tumor with the combined treatment, and pave the way to possible clinical applications of mRNA vaccines in combination with heavy ion therapy.

AI in heavy ion therapy

Artificial intelligence (AI) is already largely used in radiotherapy, especially in the segmentation and contouring imaging phase. In heavy ion therapy, we explored the use of AI to accelerate the time-consuming process of treatment planning. We developed a novel deep-learning model to select a subset of voxels in the planning process thus reducing the planning problem size for improved computational efficiency [5] (Figure 17). The novel deep-learning voxel sampling technique achieves a significant reduction in computational time with a negligible loss in the plan quality. The reduction in optimization time can be especially useful for future real-time adaptation strategies.

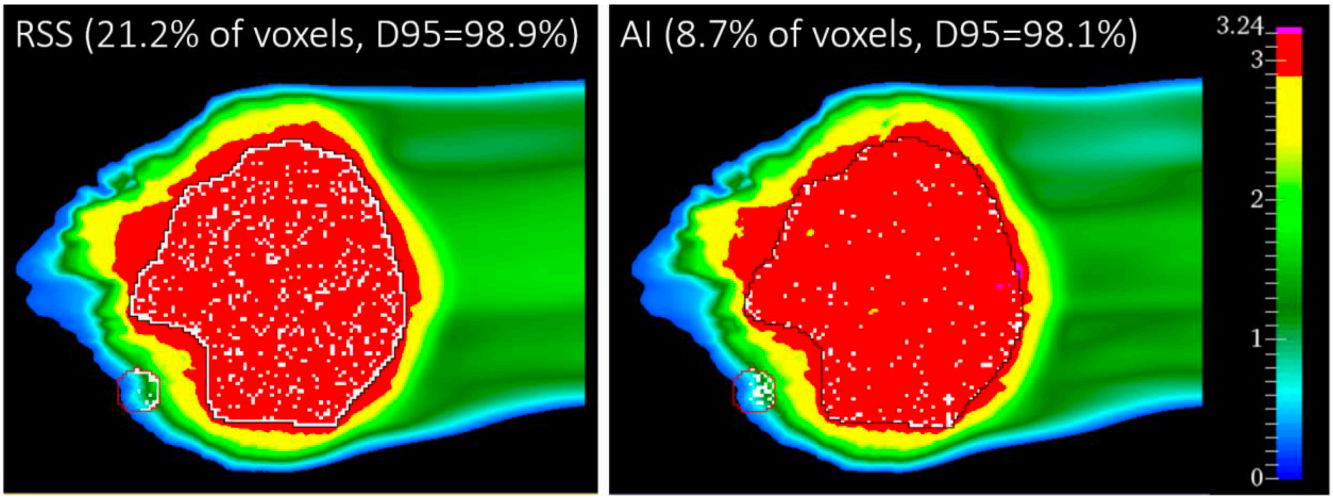


Figure 17: Comparison of the dose map for random sampling selection (left) and AI (right) produced masks for a head and neck cancer patient. Active voxels are shown in white, with the dose overlayed on the target (black contour) and brainstem (red contour; organ at risk). Figure reproduced from ref. 5, open access under CC-BY 3.0 license.

Outlook 2025

In the framework of the ESA-FAIR MoU, a new Announcement of Opportunity for Investigations of Biological and Physical Effects of Space Radiation (AO-IBPER) has been issued for the years 2026-2027. A total of 31 proposals have been submitted and will be selected by the ESA-PAC in 2025. In July the Bio-PAC will instead select the experiments to be performed in 2026-2027 in the field of particle therapy. The BARB ERC AdG will perform the final experiment for treating a tumour in vivo with radioactive ion beams in May. The new ERC CoG PROMISE will also perform the first experiments with the mixed bean ^{12}C/^{4}He. Other exciting experiments with C-ions will be about the FLASH effect with C-ions using as endpoint cognitive effects. In early May we will also use the GCR simulator for the IBPER experiments. In June, we will use the Uranium beam to test space microelectronics in the framework of the EU project RADNEXT. In August, we will also host the 5th edition of the ESA-FAIR Summer School.

Selected publications of 2024

[1] L. Schnelzauer, S. Valentin, E. Traykov, N. Arbor, C. Finck, and M. Vanstalle, “Short-lived radioactive 8Li and 8He ions for hadrontherapy: A simulation study,” *Physics in Medicine & Biology*, vol. 68, no. 5, p. 054001, Feb. 2023, doi: 10.1088/1361-6560/acb88b.

[2] V.C. Moris *et al.*, “Ionizing radiation responses appear incidental to desiccation responses in the bdelloid rotifer adineta vaga,” *BMC Biology*, vol. 22, no. 1, p. 11, Jan. 2024, doi: 10.1186/s12915-023-01807-8.

[3] N. Cogno, R. Bauer and M. Durante, “Mechanistic model of radiotherapy-induced lung fibrosis using coupled 3D agent-based and monte carlo simulations,” *Communications Medicine*, vol. 4, no. 1, p. 16, Feb. 2024, doi: 10.1038/s43856-024-00442-w.

[4] N. Salomon, A. Helm *et al.*, “Carbon ion and photon radiation therapy show enhanced antitumoral therapeutic efficacy with neoantigen RNA-LPX vaccines in preclinical colon carcinoma models,” *International Journal of Radiation Oncology, Biology, Physics*, vol. 119, no. 3, pp. 936–945, Jul. 2024, doi: 10.1016/j.ijrobp.2023.12.042.

[5] A. Quarz, L. Volz, C. H. Antink, M. Durante, and C. Graeff, “Deep learning-based voxel sampling for particle therapy treatment planning,” *Physics in Medicine & Biology*, vol. 69, no. 15, p. 155014, Jul. 2024, doi: 10.1088/1361-6560/ad5bba.

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 ultrarelativistic 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 2024, 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 semileptonic 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 mini CBM setup has been ongoing, with the objective of achieving a comprehensive demonstration of the online feature extraction capability.

The HADES collaboration, with substantial involvement from the GSI departments **HADES** and **FAIR Forschung NRW (FFN)**, has submitted a proposal for a highly competitive and innovative pion beam program for the years to come. The proposed measurements will significantly enhance HADES' contributions to baryon resonance, baryon spectroscopy, and the comprehension of the electromagnetic radiation emanating from dense and hot hadronic matter. Furthermore, the HADES collaboration has commenced an experiment to investigate Au+Au collisions at moderate energies, thereby expanding the exploration of the QCD phase diagram towards the highest baryo-chemical potentials. A substantial advancement has been made in the development of an analysis toolset, enabling the meaningful reconstruction of dynamical event-by-event multiplicity fluctuations at SIS18 and SIS100 energies. The upgrade of the drift chamber electronics has been started and two tracking planes prepared with new FEE for the beam time in 2025.

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

3.2 ALICE at GSI

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

Authors: Ana Marin, Dariusz Miśkowiec

Introduction

Out of the four major experiments at the Large Hadron Collider (LHC) at CERN, Geneva, ALICE is the one focused on the study of quark-gluon plasma (QGP) created in collisions between lead nuclei. The ALICE team at the GSI is among the largest and most impactful of the 167 groups forming the ALICE collaboration. In particular, it was strongly involved in the upgrade of the ALICE Time Projection Chamber (TPC) [1]. The upgrade increased the maximum data-taking rate by two orders of magnitude in preparation for the LHC Run 3 (2022-2026). Another important upgrade consisted in replacing the vertex detector by one with better resolution, more layers, and reduced distance from the interaction vertex (ITS2) [2].

In the spring and summer of 2024 ALICE was measuring pp collisions at $\sqrt{s}$ = 13.6 TeV. In November 2024 the LHC delivered two weeks of Pb-Pb collisions at its maximum energy, $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV, and at an unprecedented luminosity. For the first 1-2 hours of each LHC fill, the Pb-Pb collision rate was leveled at 50 kHz by displacing the beams. For the rest of the fill, typically 5-6 hours, the rate was dropping exponentially as the beams stored in the LHC were getting depleted by interactions. The ALICE apparatus, and in particular the upgraded TPC, was able to cope with sustained periods of 50 kHz interaction rate. In total, 12 billion Pb-Pb collision events were recorded, surpassing expectations. Exotic particles with high potential impact on the understanding of the strong interaction are now available in large quantities, e.g. 10^6 Λ_c baryons. Two-particle correlations involving rare species like D^0 or J/ψ are becoming measurable.

The calibration of data collected under such conditions is notoriously difficult. The GSI group continues playing a leading role in the calibration of the TPC tracking and particle identification. The main challenge here is the overlap between events: with Pb-Pb interactions happening on average every 20 microseconds and the maximum electron drift duration of 100 microseconds, the response of the detector to a particle is affected not only by other particles emitted in the same interaction but also by interactions happening before and after the event of concern. In particular, the positive ions created in the gas amplification accumulate in the TPC volume and create an electric field that distorts the trajectories of the drifting electrons. The resulting space-charge distortions of the reconstructed particle tracks are shown in Figure 18. For some types of analysis, the present quality of the calibration is already sufficient. In fact, 18 of the 34 oral presentations from ALICE in the major conference of the field, Quark Matter 2025 in April 2025, showed already results from Run 3. The calibration is ongoing and further improvements are expected.

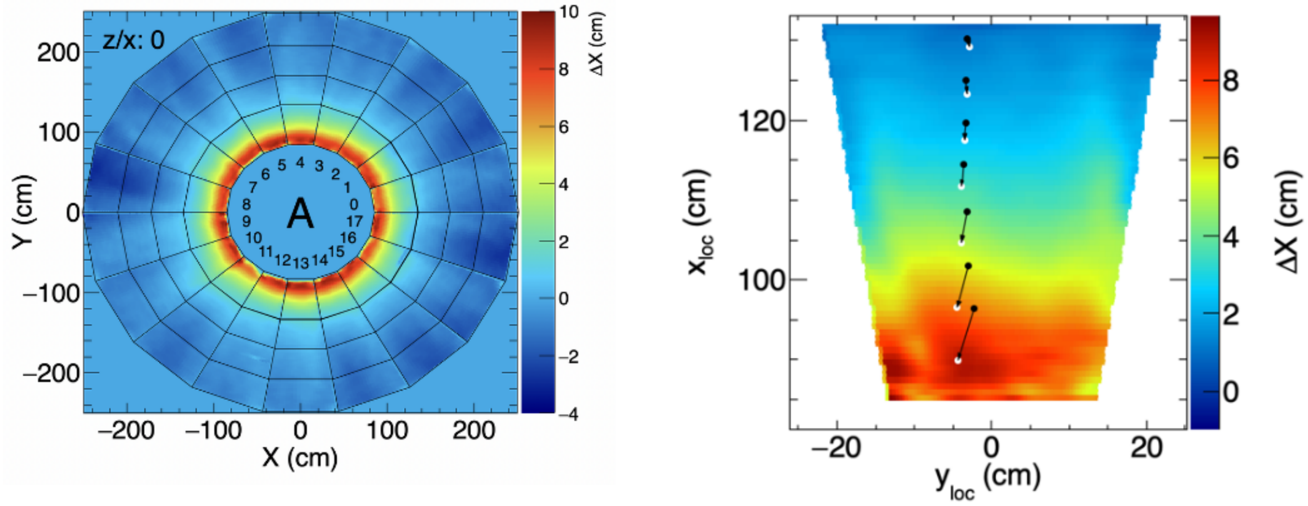


Figure 18: Left: Space-charge distortion (SCD) correction map in global coordinates. Distortions by up to ~10 cm are observed. Right: Enlarged view of an SCD correction map at small radii in one sector, showing the position of clusters before and after correction. Fluctuations are measured and corrected every millisecond. The residual distortions are O(1 mm).

Selected highlights in 2024

In 2024, ALICE submitted 43 journal articles. In eight of them members of the ALICE team at GSI were directly involved in the analysis and/or writing. In the following we briefly discuss selected results from these papers and from ongoing analyses.

The ALICE team at GSI is particularly deeply involved in the analysis of heavy flavors. Hadronic and leptonic decays of the Ω_c baryon have been studied in Ref. [3]. The production cross sections and the ratio of branching fractions $\Omega_c \rightarrow \Omega^- e^+ \nu_e$ and $\Omega_c \rightarrow \Omega^- \pi^+$ are shown in Figure 19 left.

Contrary to the assumption commonly held for several decades, hadronization is not universal but depends on the environment. In fact, the hadronization of charm into baryons is enhanced in hadronic collisions compared to $\mathrm{e^+e^-}$ and $\mathrm{e^-p}$. The ALICE measurement of the Ξ_c^0/D^0 ratio in p-Pb interactions lies more than an order of magnitude higher than model calculations tuned to reproduce e^+e^- [4]. This is shown in Figure 19 right. Quark coalescence has been proposed as a possible additional mechanism of baryon production in hadronic collisions. Measurements with the large Run 3 and Run 4 data sets with improved pointing resolution will allow for strong constraints on the charm and beauty hadronization mechanisms in high energy pp and Pb-Pb collisions.

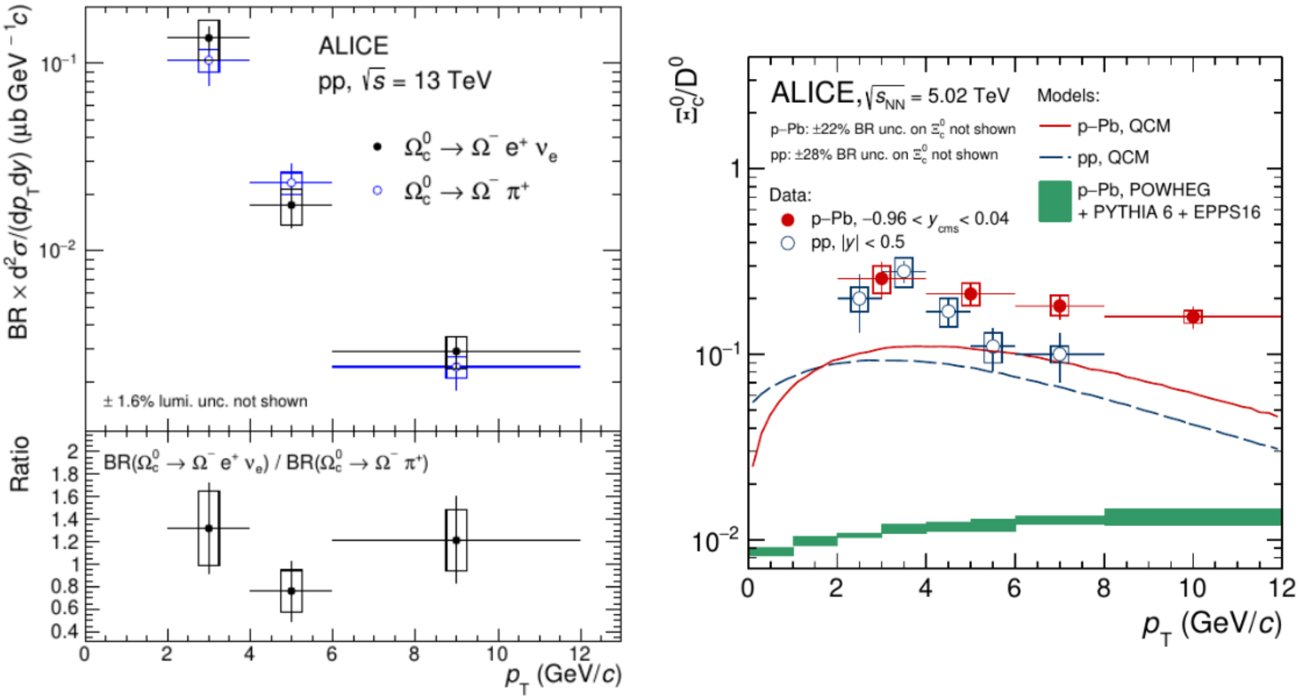


Figure 19: Left: p_T-differential production cross sections of inclusive Ω_c baryons multiplied by the branching ratios (BR) for $\Omega_c \to \Omega^- e^+ \nu_e$ and $\Omega_c \to \Omega^- \pi^+$ in pp collisions at $\sqrt{s} = 13$ TeV, and the ratio of the two decay channels [3]. Right: Ξ_c^0/D^0ratio in pp and p-Pb collisions, compared to model calculations [4].

Switching the focus from heavy to light quarks, the momentum-differential invariant cross sections of π^0 and η meson production were measured for pp collisions at $\sqrt{s}$ = 13 TeV at midrapidity ($|y| < 0.8$) [5]. The measurements span a wide range of transverse momentum and are presented as a function of charged-particle multiplicity (Figure 20). These results allow for the background estimation in the analysis of direct photons at low transverse momentum in inelastic pp collisions, as well as studies of direct-photon production as a function of event multiplicity [6].

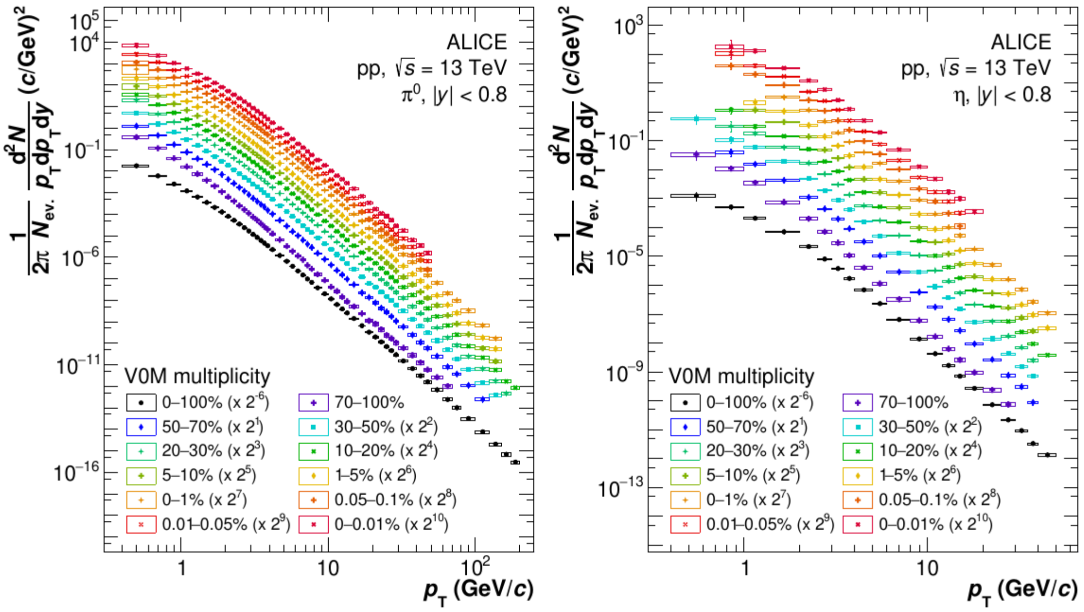


Figure 20**:** Invariant differential yields of π^0 and η mesons in inelastic pp collisions and in several charged-particle multiplicity classes. Spectra are scaled for better visibility. A hardening of the π^0 and η spectra with increasing charged-particle multiplicity is observed [5].

The hypertriton $^{3}_{\Lambda}\mathrm{H}$ is a loosely bound hypernucleus consisting of a deuteron and a Λ hyperon. Thanks to the high statistics already collected in Run 3 and the excellent spatial resolution of the new ITS2 detector, ALICE can now reconstruct the hypertriton via its three-body decay $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$. The hypertriton can be tracked through the first three layers of the ITS2 before decaying, which significantly improves the pointing resolution of the reconstructed hypertriton candidate (Figure 21 left). The invariant mass distribution of triplets $(\mathrm{d} + \mathrm{p} + \pi^-)$ tracked in the ITS2 is shown in Figure 21 right. The background-subtracted spectrum shows a peak at the expected hypertriton rest mass [7].

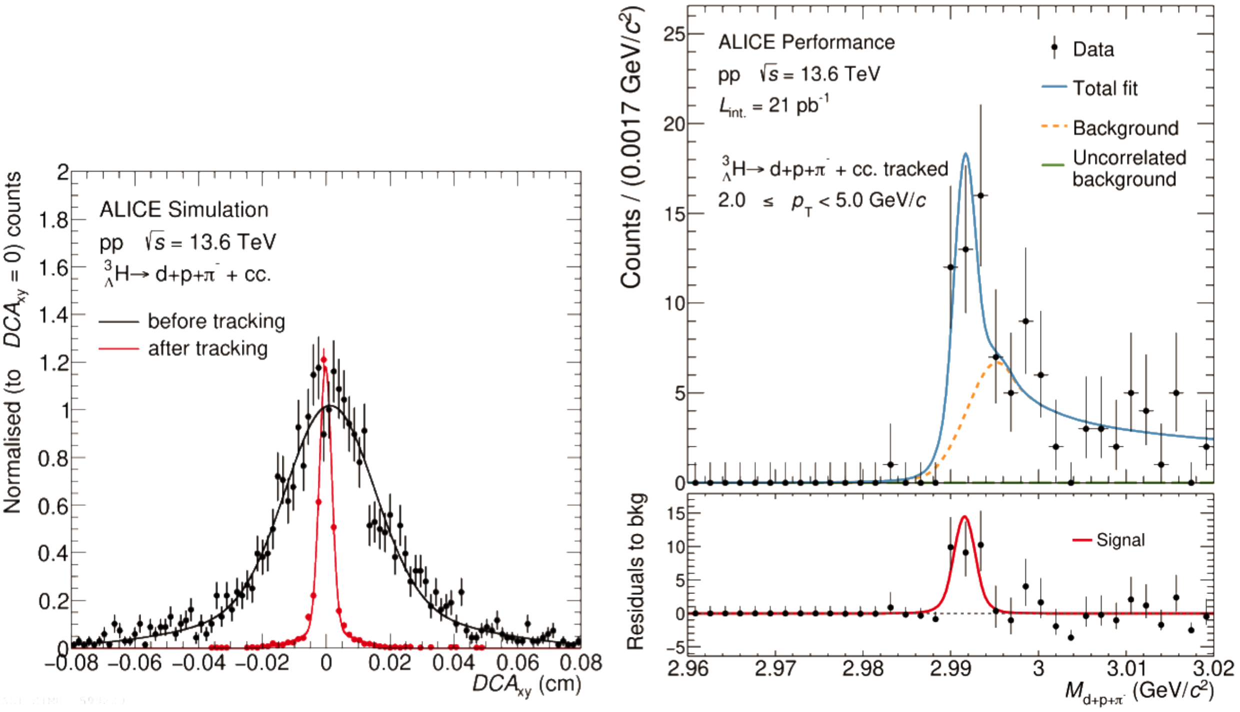


Figure 21: Left: Distance of closest approach (DCA) to the primary vertex (PV) in the transverse plane of three-body decayed hypertritons reconstructed only from their measured daughter trajectories (black markers) or tracked in the new inner tracking system ITS2 (red markers). Right: Upper panel: Invariant-mass distribution of triplets tracked in the ITS2 (black markers) fitted (blue line) using double sided Crystal Ball functions for the signal and the correlated background and a first order polynomial function for the uncorrelated background. Lower panel: Background-subtracted spectrum (black markers) and the hypertriton signal fit function (red line).

Upgrades

Alongside with its participation in the ongoing run, the ALICE team at GSI is actively involved in the development of new technologies for the bent-silicon vertex detector ITS3 of ALICE and the all-silicon outer tracker of ALICE 3 [8], planned to be deployed in 2026-2028 and 2034, respectively. This work is reflected in recent publications [9], [10], and [11].

Selected publications of 2024

[1] J. Adolfsson *et al.*, "The upgrade of the ALICE TPC with GEMs and continuous readout," *JINST*, vol. 16, no. 3, p. P03022, 2021, doi: 10.1088/1748-0221/16/03/P03022.

[2] S. Acharya *et al.*, "ALICE upgrades during the LHC Long Shutdown 2," *JINST*, vol. 19, no. 5, p. P05062, 2024, doi: 10.1088/1748-0221/19/05/P05062.

[3] S. Acharya *et al.*, "Measurement of Ω_c^0 baryon production and branching-fraction ratio BR($\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$) / BR($\Omega_c^0 \rightarrow \Omega^- \pi^+$) in pp collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev. D*, vol. 110, no. 3, p. 032014, 2024, doi: 10.1103/PhysRevD.110.032014.

[4] S. Acharya *et al.*, "Measurement of the production cross section of prompt Ξ_c^0 baryons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," *Eur. Phys. J. C*, vol. 85, no. 1, p. 86, 2025, doi: 10.1140/epjc/s10052-024-13531-w.

[5] S. Acharya *et al.*, "Light neutral-meson production in pp collisions at $\sqrt{s} = 13$ TeV," Nov. 2024, doi: 10.48550/arXiv.2411.09560

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[9] G. A. Rinella *et al.*, "Time performance of Analog Pixel Test Structures with in-chip operational amplifier implemented in 65 nm CMOS imaging process," *Nucl. Instrum. Meth. A*, vol. 1070, p. 170034, 2025, doi: 10.1016/j.nima.2024.170034.

[10] G. A. Rinella *et al.*, "Characterization of analogue Monolithic Active Pixel Sensor test structures implemented in a 65 nm CMOS imaging process," *Nucl. Instrum. Meth. A*, vol. 1069, p. 169896, 2024, doi: 10.1016/j.nima.2024.169896.

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3.3 CBM at FAIR

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

Authors: Alberica Toia (GSI & University of Frankfurt), Johann Heuser, Uli Frankenfeld, Christian Sturm, Volker Friese

Highlights & Activities in 2024

Series assembly of detector modules and ladders for the CBM Silicon Tracking System

The Silicon Tracking System (STS) [1] (depicted in Figure 22) is the core detector of the CBM experiment [2][3] to identify the charged particles that are produced when the nuclear beams from the SIS100 accelerator interact with the target. Installed in the gap of the CBM super conducting dipole magnet, STS is the experiment's sole detector to determine the particles' momenta. STS is a highly granular, low-mass and fast detector to fulfill the CBM physics mission by tracking up to 1,000 charged particles per interaction with a rate of up to 10 MHz. Its eight tracking stations are comprised of 876 detector modules, built from double-sided silicon microstrip sensors (see Figure 23) equipped with self-triggering front-end electronics attached to the sensors via ultra-low-mass micro cables. Up to 10 modules are arranged onto lightweight carbon fiber support structures, forming a total of 106 detector ladders (see Figure 24) which are then mounted onto the mechanical units of the tracking layers. Cooling of the sensor - mandatory to counteract thermal runaway is achieved with a liquid assisted air-cooling system [4].

All components for the series production of the detector modules and ladders are ready. This includes more than thousand sensors, 14,000 front-end ASICs to read out 1.8 million strip channels, hundreds of front-end electronics boards, the mechanical components of ladders as well as thousands of microcables allowing to locate the read-out and powering electronics at the periphery of the detector ladders.

In December 2024, the production readiness review of module ladder assembly was successfully carried out, addressing the performance of module assembly after a large statistic (328 modules, 37%) produced. 26 of those modules were integrated on three initial ladders. Full functionality of the modules during and after assembly and when mounted on the ladders was confirmed. The review recommended swift continuation of series assembly. As of April 2025, more than 454 modules (52%, assembly centers GSI and KIT) and 7 ladders (7%, integration site GSI) have been produced. Final qualification is being carried out at GSI involving personnel including students from the project teams in Germany, Poland, Ukraine and Japan.

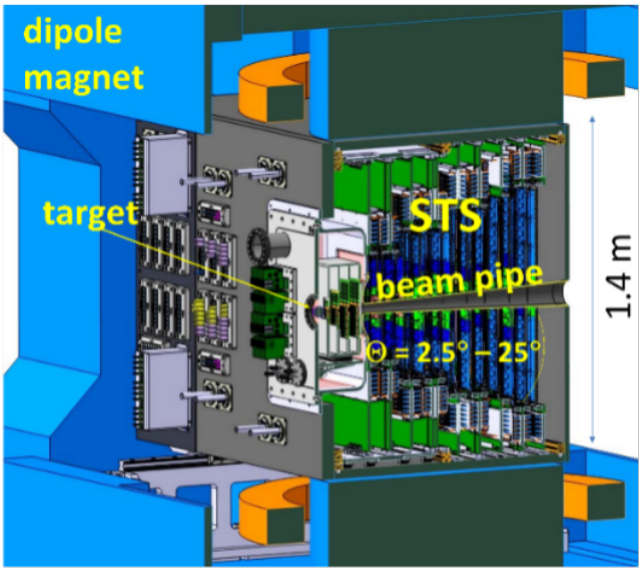

Figure 22: CAD model of STS in the dipole magnet

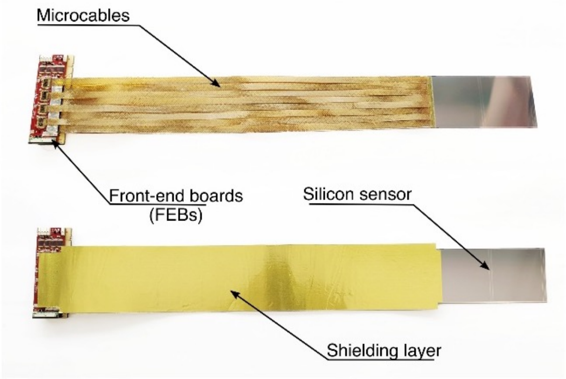

Figure 23**:** Detector module, the functional unit of STS

Figure 24: Detector ladder with 10 modules on a low-mass carbon fiber carrier

STS Operational Performance Studies

Progress in the studies of STS performances address mostly the spatial resolution and the vertex reconstruction. This was done with the data collected in May 2024 at the mCBM setup, profiting the setup with 3 STS stations. The evaluation of the single hit spatial resolution in a sensor requires the measurement of the differences between the measured impact points in the Device Under Test (DUT) of the particles and the real ones. Good track candidates are selected using 4D CA-tracking with TRD and TOF support to suppress fakes. The point in the mid STS station, taken as DUT, is then compared to the straight-line extrapolations defined by the points in the first and last STS stations. The width of the residual distribution, shown in Figure 25, combines detector resolution, tracking precision, and multiple scattering. STS resolution is extracted via Gaussian fits and corrected for misalignments, achieving values near the expected 17µm.

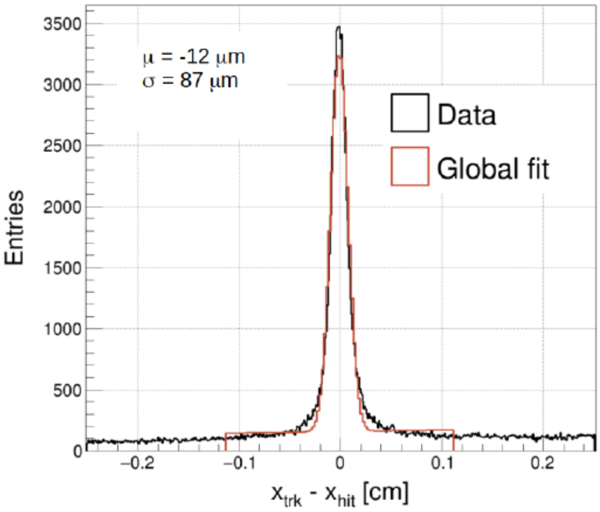

Figure 25: Unbiased hit-track residual distribution for a selected sensor module. The distribution is fitted by a Gaussian plus a second-order polynomial.

The vertex reconstruction is performed with two methods. In the first one every pair of hits in different stations forms a segment that can be extrapolated and projected to the target plane. The distribution of all tracklets extrapolations allows to reconstruct the beam spot. The second method provides an event-by-event collision point, reconstructed using the Point of Closest Approach (PCA) method by averaging valid track pair PCAs. The distribution is shown in Figure 26. Comparing the PCA method to the Beam Spot mean, show differences of only 50 µm in x and 400 µm in y.

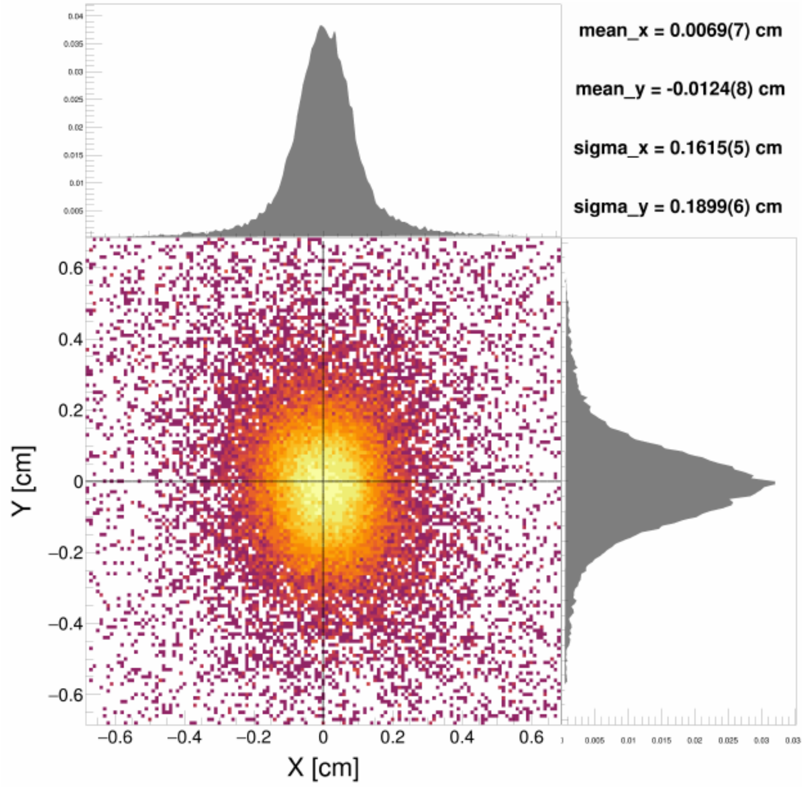

Figure 26: XY projection of the event primary vertex, together with one dimensional distributions in X and Y, respectively. The mean and the width of the distributions, obtained from a Gaussian fit, are displayed in the top right panel.

FAIR Phase-0: The mCBM campaign 2024

Major upgrades of the detector systems were performed for the campaign 2024: a third station was added upstream to the Silicon Tracking System (STS), the Transition Radiation Detector system (TRD2D and TRD1D) was equipped with pre-series components, the RPC modules within the Time-Of-Flight (TOF) wall were reconfigured and a second RPC wall added. Furthermore, two new test systems were integrated downstream the TOF wall, consisting of prototype modules of the Forward Spectator Detector (FSD) and of the (Jülich) Neutron Calorimeter (NCAL). The ROOT geometry of the mCBM 2024 setup is depicted in the left panel of Figure 27, as well as photographs are shown of the corresponding mCBM setup, as of June 21, 2024 (middle and right panel).

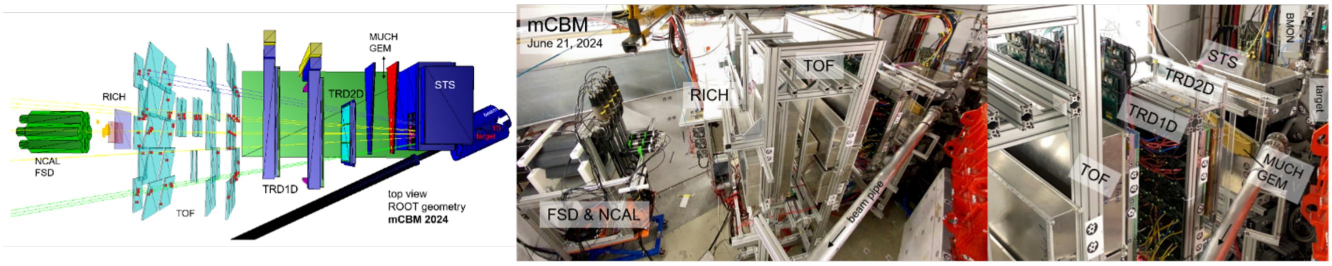

Figure 27: Root geometry of the mCBM 2024 setup (left panel) and photographs of the mCBM setup 2024 at the target station HTD, as of June 21, 2024, middle and right panel

Although first beam tests dedicated to the TOF system were carried out in December 2023 during the machine engineering run, the upgraded mCBM setup was commissioned with beam end of March’24, taking Au+Au collisions at 1.23 GeV per nucleon. Here, first experiences with a newly developed prototype system for the CBM online reconstruction and selection were gained during the commissioning phase. In March’24 as well, benefitting from the high-intensity Au beam, rate scans and ageing studies could be performed for the detector systems under extreme conditions with collision rates up to 10 MHz (and even beyond). The main high-rate detector studies with U beam, scheduled for June’24, had to be shifted into 2025 due to a HV breakdown of the SIS18 electrostatic extraction septum.

Benchmark runs, dedicated to the reconstruction of rare Λ baryons, were taken in Ni+Ni collisions at three kinetic projectile energies of 1.23, 1.58 and 1.93 GeV per nucleon in May’24. Collision system and projectile energies correspond to data published by the FOPI and HADES collaboration. While the optimization of the (software-driven) detector alignment and calibration procedures are still ongoing, rare Λ baryons (benchmark observable) were reconstructed in Ni+Ni collisions at 1.93

GeV per nucleon, shown in Figure 28. Run 2984 was taken on May 9, 2024, with an averaged collision rate of 200 kHz, duration time of 2.5 h, containing approx. 1 billion collisions.

Figure 28 shows also the results of two analyses of the data w.r.t. the Lambda signal. The left-hand plot was obtained with a mCBM-specific analysis package already deployed online (FAIR MQ based); on the right-hand side, the results of the offline analysis chain using the Cellular Automaton (CA) track reconstruction and the KFParticle analysis package are shown. The latter chain is intended to be used in the full CBM experiment for data analysis and selection in real-time. A prototype for online data processing, including unpacking, local (hit) reconstruction, CA track finding, and tagging and selection of events was implemented and commissioned during the mCBM operations – an essential step towards a performant CBM online and offline data analysis chain[5]. The prototype as well as included algorithms will be further developed and optimized in particular w.r.t. execution speed to match the CBM requirements.

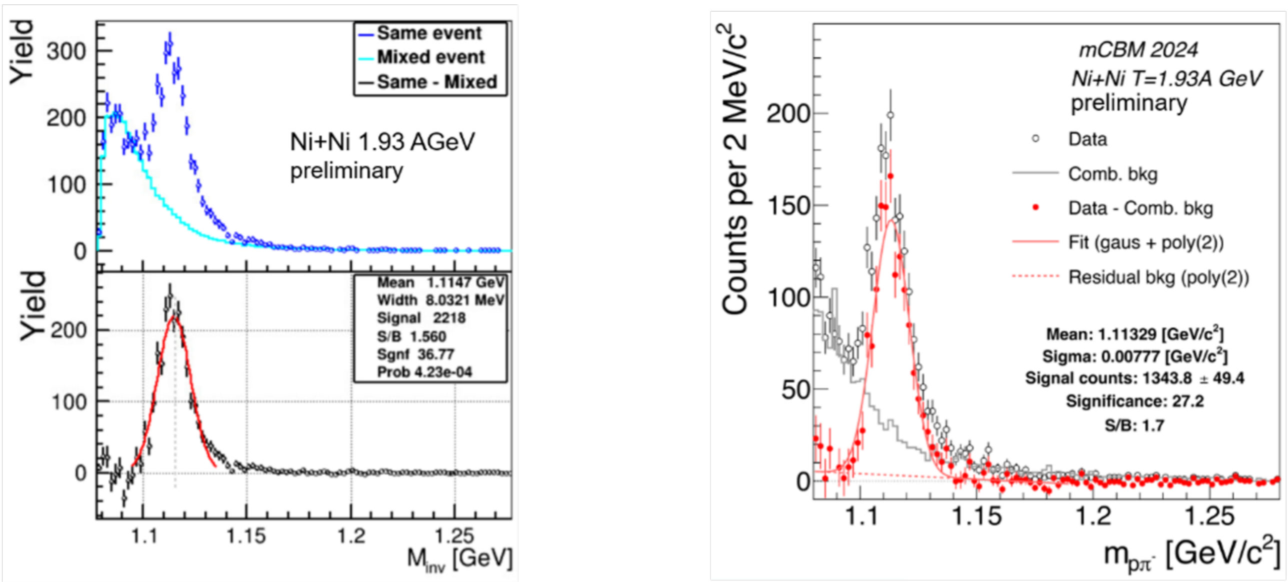

Figure 28: Preliminary results on reconstructed rare Λ baryons measured in Ni+Ni collisions at 1.93 GeV per nucleon. Run 2984 was taken on May 9, 2024, with an averaged collision rate of 200 kHz, duration time of 2.5 h, containing approx. 1 billion collisions. The left panel shows the result obtained by a FAIR MQ based, mCBM specific analysis, the result of the right panel was obtained by using the CBM offline data analysis chain including the Cellular Automaton (CA) track reconstruction and the KFParticle package.

As a pre-series production for the CBM Beam MONitor system (BMON), the mCBM setup is equipped with a fast 10 x 10 mm^2 poly-crystalline, 16-channel diamond sensor (80 µm pcCVD), mounted inside the target chamber, 20 cm upstream the target. It is read out by fast TOF electronics and measures the reaction time T0, achieving a time-of-flight resolution of about 60 ps together with the TOF detector system. During the May'24 runs an extracted BMON signal (16-channel common-or) was fed into a spill feedback loop on the Knock-Out (KO) extracted SIS18 beam to reduce the observed micro-spill structure of the slow-extracted SIS18 beam. Although the micro-spill structure was significantly improved, a nano-spill structure was observed, showing frequently short time differences between measured beam particles of shorter than 10 ns while approx. $2{\cdot}10^7$ Ni ions were extracted per 10 s spill. Due to this significant enhancement of short intervals between consecutive beam particles pile-up of the read-out chain (lost hits) was observed as well as ambiguities by assigning the correct reaction time T0 to corresponding particle trajectories. The latter challenges the reconstruction of a rare Λ signal, in particular for the lower May'24 projectile energies taken with higher collision rate. Potential solutions are under investigation.

Outlook 2025

In 2025 STS module and ladder production will commence. At the same time CBM-STS prepares further integration steps: a jig to assemble ladders to half stations is being prepared, as well a test box including cooling for subsequent testing. mCBM will continue on further detector and system tests with focus on high-rate scans.

Selected publications of 2024

[1] J. M. Heuser, "The high count-rate self-triggering Silicon Tracking System of the CBM experiment at FAIR: Design, series assembly, upgrade options," *Nucl. Instrum. Meth. A*, vol. 1066, p. 169620, 2024, doi: 10.1016/j.nima.2024.169620.

[2] C. Höhne, "Status of the CBM experiment at FAIR," *EPJ Web Conf.*, vol. 296, p. 08004, 2024, doi: 10.1051/epjconf/202429608004.

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[5] W. M. Zabołotny *et al.*, “Evolution of the data aggregation concepts for STS readout in the CBM experiment,” *JINST*, vol. 20, no. 3, p. C03018, 2025, doi: 10.1088/1748-0221/20/03/C03018.

3.4 HADES

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

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

Introduction

The HADES detector is the flagship experiment at GSI for Hadron and Strong-interaction Matter Physics at GSI SIS-18. Key features of the HADES detector are its large acceptance, high-rate capability and electron/positron identification with high purity. The major goal of the experiment activity at GSI is the exploration of the QCD phase diagram at the highest baryo-chemical potentials using rare and penetrating probes. In 2024, the program with Au+Au collisions has been continued with an energy scan towards lower beam energies. The data analysis focused on Ag+Ag data taken for the collision energy of 1.58 GeV/u, which results are now ready for publication. A focus is also the analysis of the p+p data taken at beam energy of 4.5 GeV in 2022 addressing hyperon structure physics, as well as p+p reactions at 1.58 GeV for dilepton reference spectrum measurement. The HADES collaboration has published a comprehensive document collecting many ideas for experiments with secondary pion beams. The combination of a pion beam in few GeV energy range with the high-acceptance dilepton spectrometer is world-wide unique and opens opportunities for studies of electromagnetic transition form factors of baryons in the third resonance region, studies of strangeness production through resonant channels and the investigation of in-medium modifications of vector mesons and strangeness propagation in the medium. The document, with the title pi-QCD – Proposal for Experiments at the GSI Pion Beam Facility, can be downloaded from the HADES web site.

Start of Au+Au experiment

First application of the Spill Optimisation System

The HADES experimental run targeting Au+Au collisions at various beam energies below 1A GeV has been approved and was scheduled from February 29 until March 22, 2024. For the first time, the beam was extracted from the SIS18 using knock-out extraction in combination with a feedback system regulating the apparent interaction rate in the HADES experiment. The Spill Optimisation System (SOS) uses a strip-line exciter in combination with a novel mix of periodic and random excitation signals initiating the transverse kicks [1]. As a result, the extracted beam showed very stable intensity over time, with nearly zero rise and fall time. In combination with a short time period for filling, bunching, and acceleration, a mean duty cycle of above 85 % was achieved. Figure 29 shows the excellent spill shape realised during the first days of the experiment. Besides this high duty factor, which resulted in a gain of about 40% in mean data rate compared to earlier beam times, the experiment also profited from a decoupling from intensity variations in the SIS18 and from a substantial improved micro spill structure. The latter enhanced another ~50% gain in data rate.

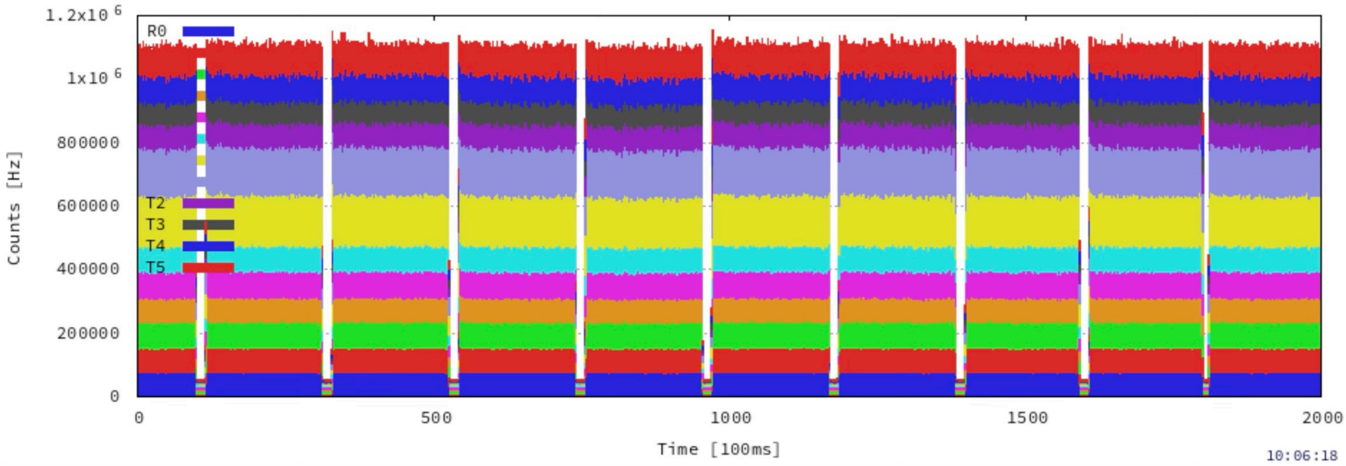

Figure 29: Mean charged particle rates in each of six sectors of the TOF and RPC detectors (colours), observed in the HADES experiment over a time span of 200 seconds. The reaction trigger was set to require a charged particle multiplicity of 20 (in acceptance) leading to a trigger rate of about 20 kHz.

Failure of the HADES cryogenic system

For the first time during the 25-year operational lifespan of the cryogenic system, a failure occurred, resulting in a leak in the largest of the five heat exchangers installed in the LINDE/SULZER TFC-20 cold box. Despite immediate attempts to rectify the leak, any subsequent operation of the cryogenic system were unsuccessful, as the remaining cooling power was insufficient to supply the super conducting magnet. The run had to be ended after 8 days and immediate actions were taken to repair the system. This was finally achieved by replacing the broken heat exchanger with an identical one that could be taken from an existing used system. By the end of the year, the whole cryogenic system could be brought back to operation. This downtime was also used to implement further monitoring of the system's state variables and to implement a new user interface to the controls of the cryogenic system based on EPICS.

Improvements of the HADES tracking system

Installation of the new MDC front-end electronics

The replacement of the 25-year-old front-end electronics of the HADES Mini-Drift Chambers (MDC) has been started by equipping the first inner-two tracking planes with new hardware. The new front-end cards, see Figure 30, feature an extreme aspect ratio to fit into the narrow space provided by the drift chamber frames, which entirely falls into the shadow region of the magnet coils. They come in two versions, processing 64 or 96 sense wires on a single board [2]. The current signals from the sense wires fed to an 8-channel amplifier-shaper-discriminator ASIC, named PASTTREC developed for the PANDA Straw Tracker by a group from AGH Cracow. The digital output, which is realized as a LVDS signal, is fed to FPGAs where their leading and trailing edge are digitized and prepared for further data transport via an auxiliary FPGA, allowing energy loss measurement by time-above-threshold. A dedicated power-on protocol was realized which allows on-the-flight power cycling and reinitialization to cope with frequent single-event-upsets in high-rate experiments. The FPGAs provide multi-hit capability, which allows monitoring random signals initiated by delta electrons produced by ions passing the target station without string interaction. Another feature of the new front-end electronics is easy maintenance, realized by a reduced number of additional daughter boards mounted right on top of the motherboard, providing all connectors and optical transceivers as well as analogue filters and spark protection.

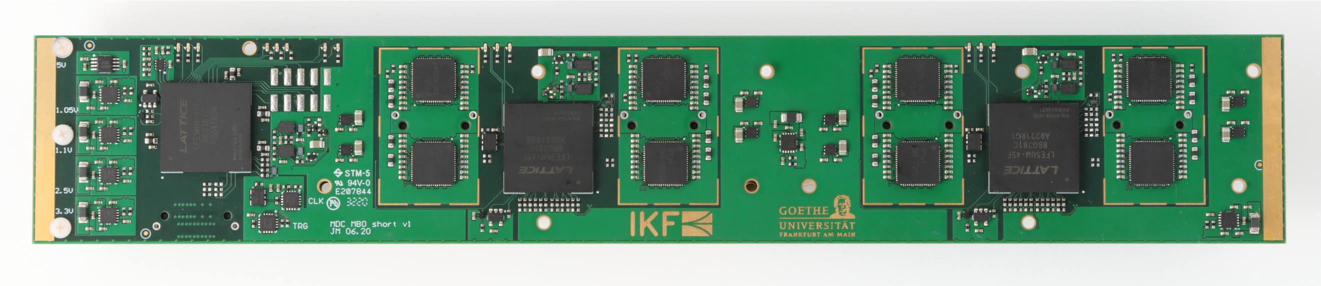

Figure 30: Photograph of the MDC motherboard front side. Shown is the 64-channel version, featuring two FPGA for time digitization and one FPGA (to the left) for data transmission and control. Also, visible are the PASTTREC ASICs for digitization, grouped each four around the FPGAs. Daughterboards are mounted to the back side of the card.

Mitigation of Malter effects for high-rate operation

A series of measurements has been conducted to optimize the stability of the inner-two MDC tracking stations, which suffer from deposits on the wires collected in up to 20 years of operation, provoking the Malter-like effects. These deposits are likely results of operating the drift chambers originally with gas mixtures containing isobutane, which is known to trigger polymerization, which is catalysed by traces of silicon compounds, found in the counting gas. Meanwhile, the chambers are operated with Ar/CO_2, considering some less favourable field strength dependence on the drift velocity. Also, stable operation without self-sustained Malter-effect could be established again by adding water vapour with volume fractions between 1000 and 3000 ppmv [3]. The stability of the drift chambers has been investigated using both an x-ray tube and test beam, and the chambers could be qualified as stable up to interaction rates (Au+Au ~1A GeV) of 20 kHz.

Highlight from data analysis

Time-differential reconstruction efficiency determination

High-rate fix target experiments with heavy ions have to cope with abundant delta electron production in the target. In particular, in the HADES spectrometer, which features a field-free inner region to enable ring imaging in the RICH detector, the tracking detectors in front of the superconducting toroid experience additional occupancy overlaying with the signals from the charged hadrons emerging from the triggered nuclear reaction. With the help of our radiation-hard time-zero detectors (T0), which record any ion crossing the target and which provide fast signals and multi-hit capability, the apparent beam intensity for any triggered event can be monitored. Based on this information, the simulation of the detector response has been extended such as to account for the event-by-event fluctuating number of overlaying delta electron events. The simulation proceeds by transporting the charged particle final states, obtained from microscopic hadronic transport simulation, and additional delta electrons from a given number of ions traversing the target within a given coincidence time, through the detector system utilizing the GEANT package. Both, the number of such ion events and their relative time distribution are randomly sampled based on the information gained from the T0 detector in the corresponding experiment. The simulation information of such a combined event is then passed to a dedicated digitiser which simulates the digital signal response in the detector cells based on the time, energy loss and position information obtained from GEANT. With this new method, a better control of systematics is achieved, which helps to improve on the respective error, often dominating over the minor statistical error from the high-statistics data.

Dilepton flow in Ag+Ag collisions

Dileptons are penetrating probes abundantly produced in the dense and hot phase of a heavy-ion collision. While produced hadrons, like in particular the lightest mesons, the pions, are leaving the interaction zone mostly at freeze-out, dileptons escape at any time they are produced and without notable further interactions with the medium. Therefore, it is not expected that such dileptons will exhibit the characteristic flow pattern seen in hadrons, escaping in a transverse direction with a clear quadrupole asymmetry, known as elliptic flow. Figure 31 shows the azimuthal asymmetry of di-electrons as a function of the invariant mass of the e^+-e^-pair, quantified by the second harmonic coefficient of the Fourier expansion (v_2). For invariant masses above 0.15 GeV/c_2, the elliptic flow coefficient is compatible with zero, a significant negative coefficient is observed for masses below. The reason is, that in this very low mass region, the dilepton spectrum is dominated by the Dalitz decay of the neutral pion. These decays proceed long after the fireball has frozen out, and hence the dileptons reflect the flow picked up by the pions during the full evolution of the fireball. The preliminary result has been presented by Niklas Schild (HGS-Hire / TU Darmstadt) in a parallel session of the Quark Matter 2025 conference.

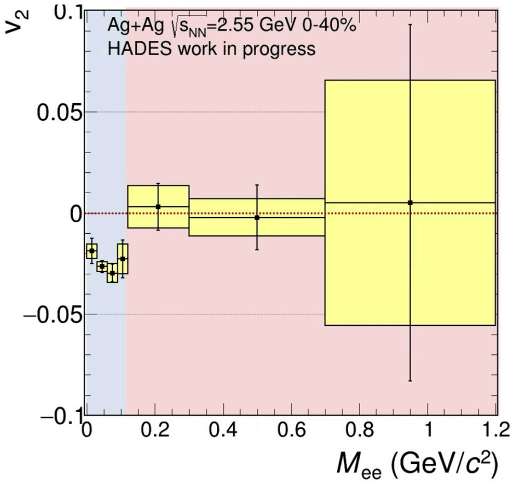

Figure 31: Elliptic flow coefficients extracted from the azimuthal distribution of emitted di-electrons for different bins of invariant pair mass. The signal has been measured for the collision system Ag+Ag at a centre-of-mass energy of 2.55 GeV per nucleon pair and for the 40% most central collisions.

Bayesian particle ID for improved event-by-event analysis

A promising tool for searching for critical phenomena in the phase diagram of strong-interaction matter are event-by-event fluctuations of the number of detected protons, which serve as a proxy for particles subject to conserved quantum numbers, like baryon number. The cumulants of various orders of the fluctuating baryon number in a sub-volume of the phase space (acceptance window) are related to the higher-order derivatives of the system's partition function with respect to the chemical potential of the related quantum number, the baryo-chemical potential. While the connection of the fluctuations to the partition function is straightforward, a number of experimental effects have to be considered and corrected for, to arrive at meaningful interpretations of the results. For example, to mitigate the effects of imperfect assignments of a particle type (PID) to a measured track, a Bayesian analysis of the experimental mass distributions has been applied for the first time to HADES data. For that, phenomenological response functions, which model the experimental mass distributions of reconstructed charged tracks, are fitted to the experimental distribution for small regions of rapidity and transverse momentum. Applying the so-called Identity Method, whereat fractional particle identities are deduced based on the fitted model functions, moments of the event-by-event particle distributions can be derived [4]. Figure 32 shows the fitted mass distribution for a selected pt-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 the Quark Matter 2025 conference.

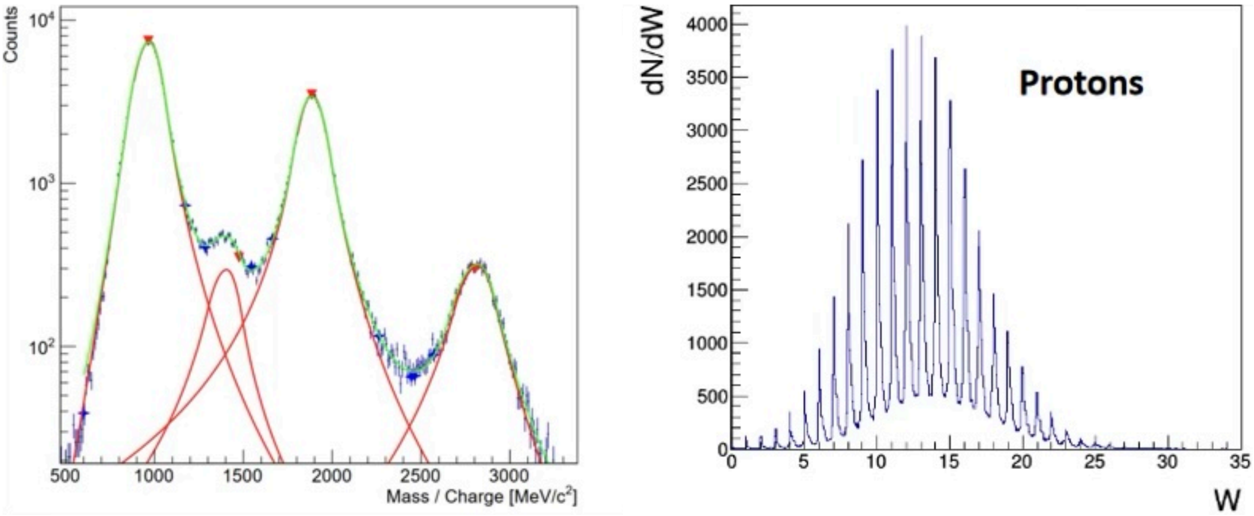

Figure 32: (left panel) Mass distribution of reconstructed charged particle tracks in the HADES spectrometer for a selected pt-y-bin. The data were taken for the collision system Ag+Ag at a centre-of-mass energy of 2.55 GeV per nucleon pair (10% most central collisions). The fractional weights in each mass bin are normalised to unity. (Right panel) Extracted event-by-event proton multiplicity distribution. The quantity W is defined as the sum of all fractional weights assigning proton ID to tracks in a given event.

Outlook 2025

Among the important events for HADES in 2025 are the continuation of the Au+Au beam energy scan, which is scheduled for beginning of May, the Quark Matter Conference in Frankfurt am Main in April, to which new analysis results have been prepared (see above), and the G-PAC which will have to evaluate the proposed pion beam program of HADES.

Selected publications of 2024

[1] Ph. Niedermayer and R. Singh, “Excitation signal optimization for minimizing fluctuations in knock out slow extraction,” *Scientific Reports*, vol. 14, no. 1, p. 10310, May 2024, doi: 10.1038/s41598-024-60966-y.

[2] J. Michel *et al.*, “New electronics for the HADES MDC drift chambers,” *Journal of Instrumentation*, vol. 19, no. 2, p. C02056, Feb. 2024, doi: 10.1088/1748-0221/19/02/C02056.

[3] C. Wendisch, C. Müntz, L. Lopes, E. Schwab, and J. Stroth, “Recovery of HADES drift chambers suffering from malter-like effects,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1064, p. 169316, 2024, doi: https://doi.org/10.1016/j.nima.2024.169316.

[4] A. Rustamov, “Fuzzy logic for reconstructing arbitrary moments of multiplicity distributions,” *Phys. Rev. C*, vol. 110, p. 064910, Dec. 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 Gorska, Alexander Herlert, Christoph Scheidenberger

The departments involved in NUSTAR (standing for "Nuclear Structure, Nuclear Astrophysics, Reactions and Superheavy Element research") pursue various research and development activities in the areas of exotic nuclei including superheavy elements, nuclear astrophysics, exotic atoms and hypernuclei; this also includes theory and applications. Most of the activities are concentrated on the GSI campus, while activities on physics and chemistry of superheavy elements are also pursued at the HI Mainz. Key activities include the preparation of NUSTAR experiments at the Super-FRS at FAIR, conducting a high-level experimental program at UNILAC and SIS18 as part of FAIR Phase-0, and supporting the international NUSTAR groups as a host laboratory. The major instruments of NUSTAR are SHIP, TASCA, FRS and related instrumentation and include the new setups of the R3B, HISPEC-DESPEC and Super-FRS Experiment collaborations for FAIR.

The NUSTAR Collaboration is in the privileged position to exploit the FAIR facility already at an early stage. The NUSTAR physics case for FAIR is currently being updated in some detail and was presented already to the Joint Scientific Council in 2024. The collaboration will concentrate on the following major topics:

- **Understanding the 3rd r-process peak** by means of comprehensive measurements of lifetimes, masses, neutron branching ratios, dipole strength, and the level structure along the N=126 isotones;
- **Probing the Equation of State (EoS)** of asymmetric nuclear matter by measuring the dipole polarizability and neutron-skin thicknesses of heavy neutron-rich isotopes
- **Study of Exotics**, such as hypernuclei with large N/Z asymmetry and nucleon excitations in nuclei

These overarching science questions need data on many nuclear physics quantities and connect all NUSTAR sub-collaborations. The first planned experiments at the Super-FRS are the fission and neutron-skin measurements of R3B that will make use of the U beams, which are expected to be available from the end of 2027. NUSTAR experiments will further benefit significantly from higher-intensity beams provided by the SIS-100 in combination with the Super-FRS for the so-called 'First Science' stage approximately one year later. Preparation to move experimental equipment to the new facility is progressing and more and more details are discussed. In the second half of 2024, significant progress has been made towards the technical realization (installation and commissioning) of NUSTAR experiments in the new FAIR buildings. A "Technical workshop for the integration of NUSTAR components at FAIR" was held at GSI in fall.

With the future experimental program at FAIR in sight, the FAIR Phase-0 campaign still offers a lot of possibilities. NUSTAR had a successful year running experiments at the existing GSI facility in 2024, and also at other laboratories using detector systems developed for FAIR. The results are presented in the following sections. Some results of the NUSTAR departments at GSI are highlighted briefly:

- Laser spectroscopy results on eight fermium isotopes from FAIR Phase-0 experiments at **SHIP**, combined with offline studies at JGU Mainz, were published in Nature in 2024. Preparatory experiments on neutron-deficient lanthanide isotopes enabled the first laser spectroscopy study of ^{152}Tm and ^{151}Er. Technical improvements enhanced the JetRIS laser spectroscopy setup's efficiency and the **SHIPTRAP** mass spectrometer's sensitivity.
- Chemical studies at **TASCA** succeeded in collecting a high-statistics data set on the formation of the $Sg(CO)_6$ complex using the sub-second isotope ^{259}Sg, which provides new insights into the formation of this molecule. The very short-lived new isotope ^{252}Rf was discovered thanks to the existence of a predicted longer-lived K-isomeric state.
- A highlight was the observation of the previously unknown isotope ^{21}Al at the **FRS**, the first unbound aluminum isotope located beyond the proton dripline. A milestone was reached when multi-nucleon transfer reactions could be carried out for the first time with slowed-down primary and secondary beams at Coulomb barrier energies at the **FRS Ion Catcher**.
- An experiment using the upgraded version of the **DESPEC** 'Hybrid' gamma-ray array setup was conducted, which focused on studies of rare-earth nuclei close to the mid-mid-shell nucleus ^{170}Dy via the world's first in-flight fragmentation of ^{170}Er ions and provided detailed nuclear structure information on highly-deformed systems.
- Two experiments with radioactive carbon isotopes have been performed at R3B using the two complementary reactions (p,2p) and (p,pd) in preparation of a systematic study along isotopic chains in different mass regions. The resulting findings interconnect the isospin dependence of short-range correlations (SRC) with the EoS of neutron-rich matter at higher densities, where SRCs play a larger role.

The FAIR Phase-0 program is extremely valuable for allowing forefront scientific achievements. In preparation of forthcoming experiments with exotic nuclei at FAIR Early Science and First Science, the current activities at UNILAC and SIS-18 and to some extent at other facilities worldwide simultaneously serve development and testing of detectors, algorithms and data analyses and for the training of next-generation scientists for the new experiments at FAIR. In a similar way, the research activities on physics and chemistry of superheavy elements are precursors of new experiments at the HELIAC, which is under construction jointly be GSI and the Helmholtz Institute HIM in Mainz.

Important collaboration meetings were – as every year – the NUSTAR Annual Meeting in spring and the NUSTAR Week in fall. From February 26 to March 1, the NUSTAR Annual Meeting took place at GSI. More than 150 registered participants on-site, as well as more than 50 participants connected on-line, discussed the present status of FAIR and NUSTAR and re-iterated the scientific possibilities during the FAIR Phase-0 program at GSI and future operation of the detector systems at FAIR. The NUSTAR Week 2024 took place October 7-9 at GSI. More than 100 participants (on-site and connected on-line) discussed in plenary talks, business meetings, and a dedicated workshop the Early Science and First Science staging steps of FAIR and opportunities for NUSTAR to perform experiments during that time.

During the 2024 NUSTAR Annual Meeting, the FAIR-GENCO awards were presented. The keynote lecture was delivered by Prof. em. Juha Äystö (University of Jyväskylä, Finland) on "Precision experiments with stopped exotic nuclei." The FAIR-GENCO Young Scientist Award was presented to Dr. Ali Mollaebrahimi (University of Giessen) for his work on nuclear structure using time-of-flight mass spectrometry techniques at the FRS Ion Catcher and the TITAN facility at TRIUMF. Several new FAIR-GENCO members were also honored. At the conclusion of the meeting, the FAIR-GENCO vice presidency transitioned from Wolfram Korten (CEA Saclay) to Zsolt Podolyak (University of Surrey), the new chair of the Board of Representatives of the NUSTAR Collaboration.

A key activity in 2024 was the preparation of the "Status Report 2021-2023," outlining the contributions of NUSTAR to the Topic "Cosmic Matter in the Laboratory" of the Program "Matter and the Universe" in the Research Field "Matter" of the Helmholtz Association. In the last decades, the field of NUSTAR science has tremendously advanced due to the advent of radioactive ion-beam facilities and intense stable beams, which allowed the production and study of exotic nuclei, i.e. short-lived nuclei far-off stability, and superheavy elements. These studies led, for instance, to the discovery of new chemical elements, novel magic numbers in nuclei with large neutron excess and have advanced our understanding of nucleosynthesis processes in the Universe.

At the various meetings of the NUSTAR Collaboration, also the time frame of the next "Program-Oriented Funding (POF)" period (2028-2034) at GSI was highlighted, which will cover the commissioning phase and first years of operation at FAIR. For producing a prioritized technical roadmap of all necessary accelerator developments and upgrades, the requirements of the NUSTAR collaboration were collected by the NUSTAR Collaboration Committee and submitted for inclusion into the GSI roadmap for Accelerator Operation and Development.

For the next few years, the main challenge for all future activities is the preparation and commissioning of the new NUSTAR experiments at FAIR for Early Science, First Science and beyond until the completion of the Modularized Start Version (MSV). Research on the heaviest elements will focus on the detailed exploration and expansion of the known territory of the island of enhanced stability to map its topography and extension; this program will benefit from the increased beam intensities provided by the HELIAC accelerator, which is under construction.

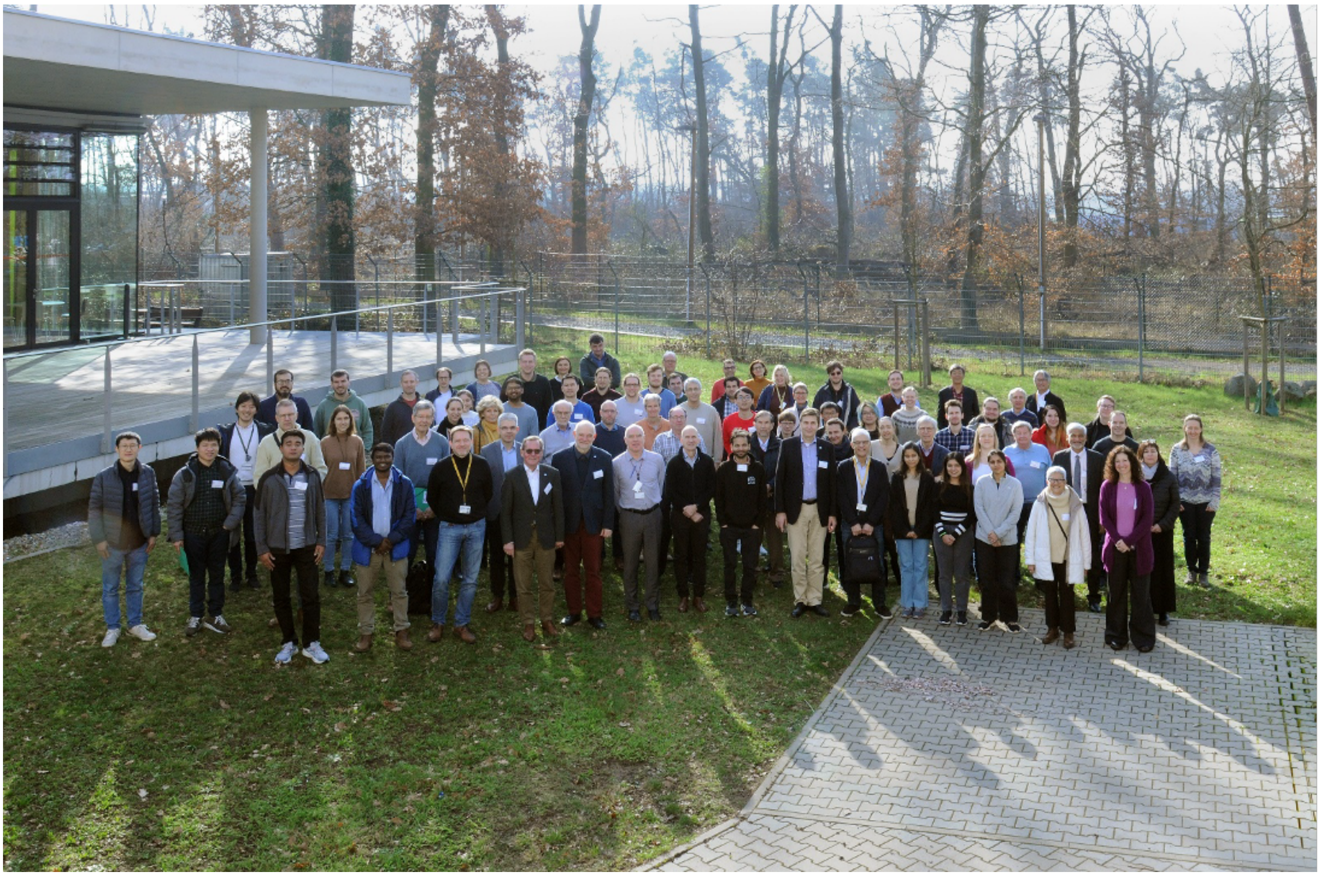

Figure 33: The on-site participants of the NUSTAR Annual Meeting 2024 at GSI-FAIR (Photograph: G. Otto, GSI).

4.2 FRS/Super-FRS

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

Authors: Daler Amanbayev, Timo Dickel, Hans Geissel [*], 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

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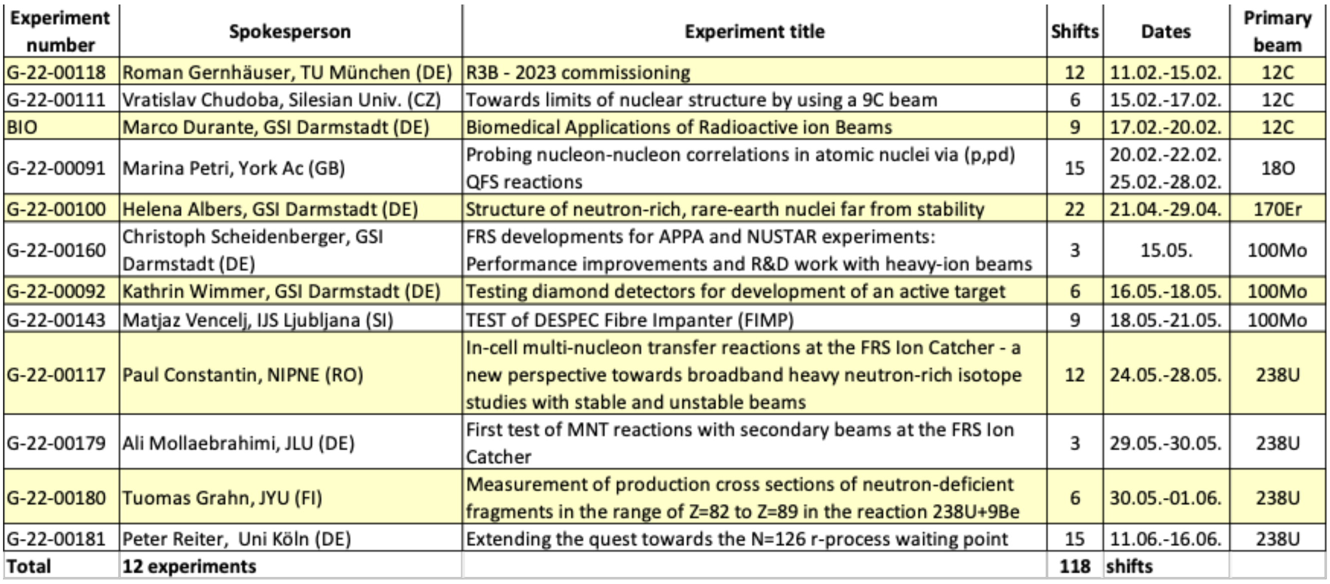
Introduction

The department NUSTAR FRS/Super-FRS Experiments is central to the NUSTAR Collaboration; it is integral part of the Super-FRS Experiment Collaboration; its members perform pilot experiments at the FRS of GSI and at other facilities; they develop instrumentation and prepare for forthcoming experiments at the Super-FRS of FAIR. The science activities focus on the exploration of exotic nuclei using various experimental approaches and reach up to bio-medical applications with radioactive beams.

The department is making the FRS available as a user facility for many experiments with relativistic radioactive beams and is upgrading it continuously; the department enables the experiments with exotic nuclei at SIS-18 of the NUSTAR Collaboration and the APPA Collaboration; these activities are described in the first paragraph. The second paragraph describes how the FRS and its ancillary detectors are used—together with and in the framework of the Super-FRS Experiment Collaboration—for the department members' own research goals; these also include complementary research activities at the UNILAC and at other laboratories. The third paragraph contains developments in preparation for FAIR experiments.

Experiments with exotic nuclei at SIS-18

The main instrument of the department NUSTAR FRS/Super-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 experiments at the Super-FRS. The FRS has three branches and the exotic nuclei can be guided to various destinations: (i) the main branch, with the experiment setups of the HISPEC/DESPEC and of the Super-FRS Experiment Collaboration, (ii) the storage-ring branch, where the NUSTAR and APPA Collaborations perform precision experiments with stored secondary beams in the ESR-CRYRING complex, and (iii) the target-hall branch, where the R3B experiment is located and where joint BARB (bio-medical applications with radioactive beams) experiments are executed in Cave-M. In 2024, the NUSTAR Collaboration has taken advantage of the FAIR Phase-0 and performed a number of experiments, which are listed in Table 3.



Experiment number	Spokesperson	Experiment title	Shifts	Dates	Primary beam
G-22-00118	Roman Gernhäuser, TU München (DE)	R3B - 2023 commissioning	12	11.02.-15.02.	12C
G-22-00111	Vratislav Chudoba, Silesian Univ. (CZ)	Towards limits of nuclear structure by using a 9C beam	6	15.02.-17.02.	12C
BIO	Marco Durante, GSI Darmstadt (DE)	Biomedical Applications of Radioactive ion Beams	9	17.02.-20.02.	12C
G-22-00091	Marina Petri, York Ac (GB)	Probing nucleon-nucleon correlations in atomic nuclei via (p,pd) QFS reactions	15	20.02.-22.02. 25.02.-28.02.	18O
G-22-00100	Helena Albers, GSI Darmstadt (DE)	Structure of neutron-rich, rare-earth nuclei far from stability	22	21.04.-29.04.	170Er
G-22-00160	Christoph Scheidenberger, GSI Darmstadt (DE)	FRS developments for APPA and NUSTAR experiments: Performance improvements and R&D work with heavy-ion beams	3	15.05.	100Mo
G-22-00092	Kathrin Wimmer, GSI Darmstadt (DE)	Testing diamond detectors for development of an active target	6	16.05.-18.05.	100Mo
G-22-00143	Matjaz Vencelj, IJS Ljubljana (SI)	TEST of DESPEC Fibre Impanter (FIMP)	9	18.05.-21.05.	100Mo
G-22-00117	Paul Constantin, NIPNE (RO)	In-cell multi-nucleon transfer reactions at the FRS Ion Catcher - a new perspective towards broadband heavy neutron-rich isotope studies with stable and unstable beams	12	24.05.-28.05.	238U
G-22-00179	Ali Mollaebrahimi, JLU (DE)	First test of MNT reactions with secondary beams at the FRS Ion Catcher	3	29.05.-30.05.	238U
G-22-00180	Tuomas Grahn, JYU (FI)	Measurement of production cross sections of neutron-deficient fragments in the range of Z=82 to Z=89 in the reaction 238U+9Be	6	30.05.-01.06.	238U
G-22-00181	Peter Reiter, Uni Köln (DE)	Extending the quest towards the N=126 r-process waiting point	15	11.06.-16.06.	238U
Total	**12 experiments**		**118**	**shifts**	

Table 3: FRS-experiments with radioactive beams performed in year 2024 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.

The **support of experiment groups** ranges from the physics idea 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 3 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. Special attention continues to be paid to the compatibility of all elements and subsystems of the separator with FAIR standards, especially with regard to power supplies, the vacuum system, control programs, and general infrastructure (LAN, radiation safety, general safety, access system for controlled areas). Specifically, the conversion of the magnetic power supplies to the FAIR ACCU system was almost completed in 2024, and preparations were made for commissioning of the new FAIR stepper motor controllers. Another focus of work is the **modularization** of the experiment equipment at the main focal planes (midplane, final focal plane) of the FRS. This concept was developed for the FAIR Phase-0 experiment series, where many different experiments (with individual setups) are concentrated within few months of beamtime; it has been gradually implemented over the years. Examples include the "standard-ID frame," the "user table" that can be inserted using the overhead crane, and the movable HISPEC-DESPEC platform for complex spectroscopy experiment setups at the final focus of the FRS. Construction of the module, which integrates the standard components for separation and particle identification at the central focal plane of the FRS, began in 2024. All standard detectors of the FRS (i.e., the detectors used for primary-beam monitoring and for production, separation and identification of exotic nuclei) are now on drives (including those in air), allowing for much more flexible operation within and between experiments. This significantly reduces setup times during beamtime operations and allows for more user beamtime. In general, this concept maintains and even increases the necessary flexibility (each experiment has a setup tailored to its individual measurement objective), increases reliability and readiness during conversion of setups (all components are pre-assembled, adjusted, and tested), and simultaneously reduces setup times during beamtime operations and allows for more user beamtime. A prominent, albeit extraordinary example of the flexibility of experimental setups at the FRS combined with their reliability is the WASA detector, which could be integrated into the FRS and de-installed after the completion of the experiments in 2022 within rather short time. Finally, yet importantly, the members of the department are continuously working with the in-house specialist groups to ensure compliance with and further improve all safety standards for the benefit of all experimentalists.

In year 2024, there were also many maintenance and upgrading measures in detectors, electronics, signal processing, data acquisition, and analysis systems. Many of them were tested for the first time with beam as part of the G-PAC approved experiment G-22-00160 entitled "FRS developments for APPA and NUSTAR experiments: performance improvements and R&D work with heavy-ion beams". In addition, the training sessions mentioned at the end of this section were partially conducted as part of this experiment.

On the **hardware** side, the improvements include the performance increase of the FRS data acquisition system (DAQ), and the refurbishment of standard detectors that are used for every experiment.

The overhaul of the TPC detectors, used for position measurement and tracking, is ongoing: the re-design of preamplifiers has been completed, and performance tests were performed. The preparations for building a TPC backup device have started (at present there is no replacement if one of these detectors, which are essential for operation, should fail).

In collaboration with Beam Diagnostic group and the Detector Laboratory, the electronics of the beam-profile grids was overhauled and re-calibrated. Preparations for the installation of new current profile grids were made. So far, beam alignment of fast-extracted beams for injecting exotic nuclei into the ESR has been hampered by the lack of an angle measurement in the FRS central focal plane and must be improved for future experiments at the ESR-CRYRING complex.

At the first focal plane, a new scintillator detector was installed in vacuum, which serves for ToF measurement in the second dipole stage of the FRS. The new MUSIC detectors, designed and constructed by the GSI Detector Laboratory, are also in test and almost ready for routine use for Z-identification. They will, together with new time-of-flight detectors, extend the experimental capabilities, as they enable the complete identification of ions in the first half of the FRS; this opens new perspectives, especially for experiments using the first half of the FRS as analyzer and the second half of the FRS as a high-resolution momentum spectrometer.

The FRS data acquisition system is based on four VME crates and uses the GSI Multibranch System (MBS): it is modular in design, consists of several standard crates, and can be expanded with several detector- or experiment-specific stations, such as the MR-TOF or R3B crate or other, experiment-specific user crates. To increase the rate of accepted triggers, it was equipped with new crate controllers (in cooperation with the EE department), and the experiments in 2024 ran flawlessly, with a factor of ~2.5-3 improvement in maximum data acquisition rate. This enables more efficient use of beam intensity and available measurement time, which all experiments benefit from. For the online analysis of micro- and macro-spill structure, appropriate analysis routines were implemented, and the corresponding displays were made available to the HKR as a monitor.

A key goal of the **software**-based data management activities is (i) the bundling or centralization of all information related to the experiments with exotic nuclei, (ii) the improvement of the (external, low-threshold) access options of experimenters to information, data and metadata needed for the preparation, execution and evaluation of their experiments, and (iii) the experiment-specific, individual archiving of, for example, different versions of the data acquisition and data analysis programs. Worth mentioning here is the implementation of a data platform (https://lxfrs.gsi.de) and corresponding structures, which can be easily accessed anytime and from anywhere in the world to provide access to experiment-specific information such as LISE++ simulations, technical drawings and setup mock-ups, copies of the logbook, etc. These upgrades, in cooperation with IT department, are embedded in GSI's Open Science concept and the implementation of the F.A.I.R. Data Management principles, as well as in the preparation of a Europe-wide, uniform concept for data management plans for user groups of the TNA facilities (a work package within the EURO-LABS framework, to which the FRS/Super-FRS Experiments department contributes, together with the respective specialist groups at GSI).

In the course of preparing experiments that can be controlled remotely from the FAIR Control Center (FCC), the development of the so-called "Virtual FRS Messhuette," a web-based interface, is particularly worth mentioning. The "Virtual FRS Messhuette" provides access to the information available in the real FRS Messhütte, but online. For instance, accelerator and beam status, separator and experiment status, scalers, settings, detector voltages, etc. can be monitored. This enables a simple, quick overview of the status of FRS experiments and is advantageous because the FRS shack is small, experiment collaborations are growing ever larger, and the experimenters can monitor from their office, remotely, or even from home. This feature can be a big practical advantage for rapid diagnosis when experimentalists can investigate without having to get to GSI. In addition, it contains logging of selected information by Grafana. The first practical test of the "Virtual FRS Messhuette" will take place during the experiments in 2025.

Fragment separators are at the heart of modern nuclear science research around the world; these are not simple beamlines but they can deliver one specific isotope from a soup of literally a thousand very similar products emerging from the production target. Successful experiments with exotic beams require dedicated specialized teams. The **NUSTAR Beam Team** has played a key role in preparing and conducting the experiments depicted in Table 3. With changing composition, the NUSTAR Beam Team is a collaborative effort as it consists of several members of the NUSTAR Collaboration and its sub-collaborations, particularly members of in-house groups such as Nuclear Spectroscopy and Super-FRS Project group and externals from the Super-FRS Experiment Collaboration. The individuals involved are thanked for their personal commitment and contribution; the support provided by many collaboration partners and their contributions to the successful implementation are particularly appreciated.

An important aim is the **training** of young scientists and members of the Super-FRS Project group in preparing the forthcoming experiments of the NUSTAR Collaboration at the Super-FRS. The structured training activities, that were held for several years, are largely performed by the FRS/Super-FRS Experiments department and members of the Super-FRS Experiment Collaboration. Blended-learning methods were used: lectures and tutorials by experts (e.g., on in-flight separation), online courses (e.g., on simulation programs), practical exercises with hands-on training and "how to…" instructions (e.g., electronics, detectors, DAQ and online-analysis, FRS operation programs, safety-related matters, electronic logbook and documentation), and self-studies (e.g. using literature and documentation, web-based online-tools, etc.). A critical component of the training program was the online training with beam, which could be conducted under realistic conditions as part of the above-mentioned experiment G-22-00160. Such knowledge and experience are essential prerequisites for performing successful experimental runs at in-flight separators.

Scientific activities and results

In addition to the activities described above, the members and associates of the FRS/Super-FRS Experiments department conduct an original scientific program. The department's main scientific interests are manifested in the Super-FRS Experiment Collaboration. The science portfolio includes new physics opportunities such as exotic atoms, hypernuclei, exotic radioactivity modes, nucleosynthesis and equation-of-state of cold asymmetric nuclear matter; it also includes highly important frontiers of physics such as the search for new isotopes, determination of ground-state properties (like nuclear radii, atomic masses), and atomic collisions. The ongoing experiments during FAIR Phase-0 include both, online runs and an offline program (e.g. at the FRS Ion Catcher), and the group also participates in and contributes to experiments at other major laboratories such as RIKEN (Wako, Japan), JYFL (Jyväskylä, Finland), CERN (Geneva, Switzerland) and TRIUMF (Vancouver, Canada). Due to very limited space, recent findings and results are described only very briefly; in particular, figures have been largely omitted; details can be found in the respective publications mentioned.

Production cross-sections and yields of secondary beams

The ongoing ion source developments at GSI are of strategic importance for the whole NUSTAR Collaboration as they provide new experimental opportunities and access to nuclides, which are currently not accessible at high rates. Production cross section measurements are essential for reliable yield and rate predictions for all forthcoming experiments, including those planned at the Super-FRS at FAIR. A ^{170}Er beam was available for the first time from SIS-18 in 2024 and used successfully for the experiment G-22-00100. In a similar way and as part of the training activities in experiment G-22-00160 mentioned above, a cross section survey was conducted with the newly available ^{100}Mo beam. Figure 34 shows a summary map of the observed nuclides. Another experiment conducted in 2024, G-22-00180, aimed at the measurement of cross sections for a wide range of elements and their isotopes far-off stability, in this case with a 1 GeV/u ^{238}U primary beam on beryllium. The data are currently under analysis in a wider context, including the new-isotope-search experiments with ^{208}Pb beams performed earlier at the FRS in FAIR Phase-0.

Fission isomer studies

The resulting data provide quantitative information on the secondary-beam intensities available for future experiments, e.g., to explore the limits of existence of isotopes and the study of nuclear structure and nuclear decay properties. In addition, the population of isomers ("isomeric ratios") is of practical relevance and fundamental interest [1]. A particularly interesting object are so-called fission isomers, i.e., meta-stable excited nuclear states, which decay by spontaneous fission. First results from an FRS experiment (S-530) investigating the population of ^{236f}U via ^{238}U fragmentation and electro-magnetic dissociation reactions can provide upper limits and will be continued in summer 2025 with an improved detector setup (constructed in 2024) and longer measurement time (scheduled experiment G-22-00182).

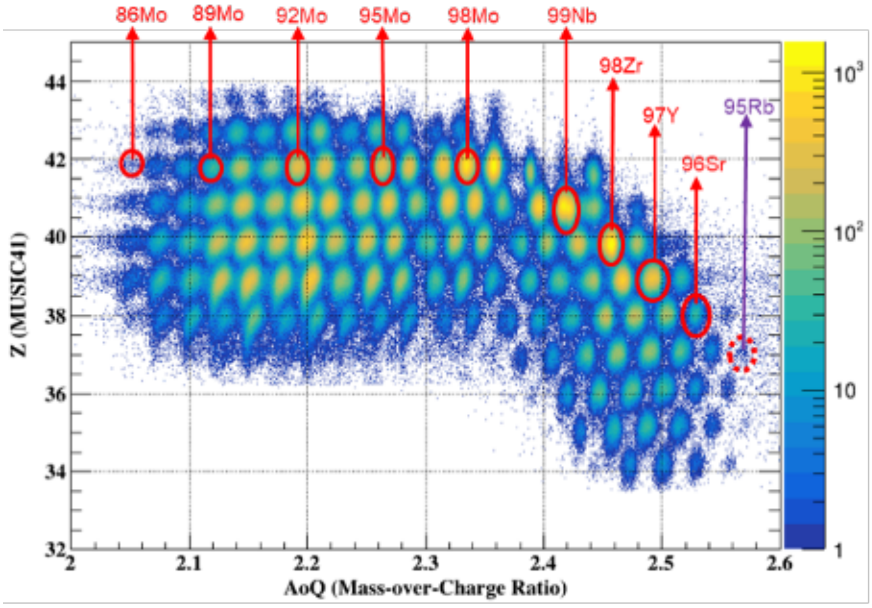


Figure 34: Online identification plot summarizing the spectra obtained in a ~10-hour beamtime cross section survey with a 500 MeV/u ^{100}Mo primary beam on beryllium. The 9 different fragment settings are highlighted (the red ellipses mark the set fragment of interest). In the short measurement time a cross section limit of few 10 nb was reached.

Matter and charge radii of dripline nuclei

Next to production yields and cross sections, reaction studies with radioactive nuclear beams provide insights to properties and structure of nuclei near the driplines. For instance, accurate charge-changing and total interaction cross-section measurements using the transmission technique yield mean-square charge radii and matter radii. The combined knowledge of matter radius and proton radius helps to determine the geometrical structure of dripline nuclei, where halos, skins and nucleon correlations prevail. The symmetry energy links e.g., neutron skins with the nuclear equation of state (EOS). Several measurements of charge-changing cross sections for neutron-rich isotopes, conducted at the BigRIPS fragment separator with its Zero Degree Spectrometer (ZDS) at the Radioactive Isotope Beam Factory (RIBF) in Japan, have been performed. The analysis yields charge changing cross section for ^{21,22,23}N and allows the first determination of their point proton root mean square radii. The combined knowledge of matter radii and proton radii in neutron-rich boron isotopes ($^{12\ldots19}$B) yields the evolution of neutron-skin thicknesses. The geometrical structure of the nuclei enables the understanding of neutron-neutron correlations and the short-range forces acting between two neutrons and the core. These findings complement the comprehensive, synthetic analysis of charge-changing cross sections measured at the FRS before FAIR Phase-0 (see [2] and references therein), for which a new approach for deducing rms proton radii from charge-changing reactions could be identified and published: a robust relationship between the scaling factor of Glauber model calculations and the separation energies of the nuclei of interest was identified, which allows to deduce proton radii for the first time from the cross sections measured on hydrogen [2].

Nuclear cross sections for bio-medical applications of radioactive beams

Another motivation for the measurement of production, charge-changing and total interaction cross sections arises in the context of bio-medical applications of radioactive beams, which are currently being pioneered at GSI in the BARB project. The members of the FRS/Super-FRS Experiments department and the Super-FRS Experiment Collaboration contribute with their expertise in precision measurements and are currently analyzing the total interaction and charge-changing cross sections of positron-emitting isotopes (such as ^{10,11}C and ^{14,15}O) with various target materials (including water) at energies that are relevant for treatment of tumors, i.e., in the energy range of 300...400 MeV/u. The data analysis is in progress. The data are crucial in heavy-ion radiation therapy because they describe the probability of nuclear reactions occurring between the heavy ions and the patient's tissues; they influence the dose distribution, range, and secondary radiation fields, affecting the accuracy and effectiveness of the treatment. Consequently, realistic cross-section data are a critical component of heavy-ion transport codes, which are used to simulate particle transport and energy deposition in tissue and ensure safety, effectiveness, and precision of radiation therapy.

In 2024, the department members contributed to the first tumor treatment using radioactive beams, which took place in Cave-M in cooperation with the BARB Collaboration (see page 25). A mouse osteosarcoma was successfully treated using a radioactive ^{11}C ion beam that was produced and separated with the FRS. The treatment with radioactive beams benefits from image-guided treatment, as the isotopes that undergo β^+-decay can be visualized *in vivo* and almost in real time *online* using positron emission tomography (PET).

Proton radioactivity of dripline nuclei

Beyond the proton dripline, the structure of nuclei and their decay properties are intimately connected with the limits of existence. The most exotic nuclear systems are expected to exhibit only continuum spectra without resonances. At the FRS, such phenomena can be studied with the original in-flight decay method, where the trajectories of the decay products of very exotic nuclei can be tracked with silicon micro-strip detectors. In a recent publication [3], the so far unknown isotope ^{21}Al, the first unbound aluminum isotope, located beyond the proton dripline, is reported. The ^{21}Al nucleus decays by one-proton (1p) emission, and the decay was studied by analyzing the measured angular correlations of decay products ^{20}Mg+p. The 1p-decay energies of the ground and low-lying excited states of ^{21}Al, its mass excess, and the proton separation energy $S_p = -1.15 +0.10/-0.07$ MeV were determined.

Nuclear-structure investigations via high-precision mass measurements

Precision mass measurements play an important role in the study of exotic nuclei far from stability at virtually all existing radioactive-beam facilities. In recent years, the methods for generating and manipulating thermalized exotic nuclei have been significantly improved, at the FRS primarily by leveraging the intrinsic advantages of a synchrotron-based accelerator facility. The FRS Ion Catcher is at the center of these developments, enabling higher yields, cleaner beams, and broadband mass measurements and, consequently, new scientific opportunities [4]. Recent improvements to the FRS Ion Catcher focus on a new ion source that enables more flexible and longer-term operation, as well as more precise mass measurements. Two important assets have been published in 2024, the laser ablation ion source integrated into an extension of the radiofrequency-based beamline (connecting the stopping cell and the mass spectrometer) [5] and the combined electron impact and thermal ion source [6], which is part of the MR-TOF mass spectrometer.

Two regions of the nuclear chart were examined in particular in recent years, in collaboration with the IGISOL group at the University of Jyväsylä (Finland) and at both laboratories. The first one concerns the neutron-deficient silver isotopes, highlighted by the special case of the high-spin isomers in ^{94}Ag, and first results were recently published in [7]. The other region of interest is heavy fission fragments. At IGISOL, these measurements focused on masses around A~170 and tested whether shape transitions occur in this middle shell region; also, the influence of mass on r-process nucleosynthesis was investigated [8]. Complementary to this study, a ^{252}Cf spontaneous fission source, placed in the cryogenic stopping cell of the FRS Ion Catcher, was used to probe the region of shape phase transitions in the rare-earth region [9].

Offline experiments at the FRS Ion Catcher

The radioactive ion sources in the cryogenic stopping cell of the FRS Ion Catcher enable a comprehensive scientific program even without accelerated beams from the SIS-18. This offers specific advantages, in particular the opportunity to perform long-term experiments and proof-of-concept studies. Three examples can be mentioned here very briefly.

A long-term experiment to search for the theoretically predicted but hitherto undiscovered double-alpha decay was conducted using the ^{228}Th source. Data were collected for more than four months and more than one billion decay events of ^{224}Ra, the prime candidate for simultaneous emission of two alpha particles, were detected. Details on the setup and its performance can be found in [10]; the data analysis is ongoing.

The same radioactive source was also used to produce fluorides of the thorium decay products; the generated molecules can be identified with the MR-TOF-MS, and the chemical reaction rates and their dependence on the charge state of the radioactive isotope were measured. The production and characterization of radioactive molecules is the first step toward their use in the search for the electric dipole moment of electrons and physical phenomena beyond the Standard Model. Initial results are outlined in the review article [11].

Finally, the investigations on fission products mentioned a few lines above also belong to this category of experiments.

Exotics

One of the three top priorities of the NUSTAR Collaboration is the study of "exotics": exotic atoms, hypernuclei, and the like. Two experiments were performed with the WASA-FRS combination in 2022 with the aim to produce and study light hypernuclei and to search for η'-mesic nuclei. The analysis of data taken with this complex and new setup is very complicated and still ongoing. A basic framework of a machine learning and Graph Neural Network (GNN) methods has been developed and the first results are upcoming. The progress made as well as instrumental and methodological developments can be found in several publications and conference contributions [12], [13], [14], [15], [16]. Currently, considerations for forthcoming experiments with a new, more compact setup are underway, and several Letters of Intent have been submitted to the latest G-PAC.

Towards multi-nucleon transfer reactions with secondary beams

Efforts are being made worldwide to explore regions of the nuclear map that are inaccessible using established methods. Of particular interest are neutron-rich heavy isotopes above the fission-fragment region (A>180) and neutron-rich isotopes with masses A>235, which are currently completely inaccessible. The most promising method is multi-nucleon transfer (MNT) reactions combined with gas-stopping to make the synthesized ions accessible for identification and for experiments. It is a long-term goal of the Super-FRS Experiment Collaboration to perform multi-nucleon transfer reactions with the intense beams of neutron-rich isotopes of the Super-FRS at FAIR. To this end, several approaches are being pursued: studies with stable beams at Coulomb-barrier energies to generate high-quality reaction data (e.g., at UNILAC and IGISOL), developments and tests with slowed-down SIS-18 beams to reach feasibility and gain experience, and consultations with theorists to test reaction models using new data classes. Considerable progress has been made in all three aspects over the past year: (i) a test experiment was conducted at UNILAC for a new concept for the unambiguous determination of A and Z in low-energy reaction studies, allowing the simultaneous measurement of the complete kinematic information; (ii) at the FRS Ion Catcher, the first MNT products were generated and identified using slowed-down relativistic primary and secondary beams (experiments G-22-00117 and G-22-00179) [17], thus representing a first milestone on the way towards the ultimate goal of exploiting efficiently MNT reactions with secondary beams; results of several joint measurement campaigns at IGISOL on the influence of the reaction input channel on the isomeric ratio have been published [18], [19]; (iii) the results have been used to benchmark state-of-the-art reaction models (to be published).

Technical developments for new experiments at the Super-FRS

Finally, the preparation of some novel instrumentation for new experiments of the Super-FRS Experiment Collaboration is underway. This will enable first experiments to be conducted already at the Early Science and First Science phase, respectively, which will benefit from the intense secondary beams provided by the Super-FRS at FAIR. A key activity is the development of the Cryogenic Stopping Cell (CSC) [20] for the Super-FRS Ion Catcher and the preparation of experiments with particularly neutron-rich nuclei far from stability, e.g., precision mass measurements of nuclides relevant to stellar and explosive nucleosynthesis, and the determination of beta-delayed neutron emission probabilities, with particular potential for larger multiplicities. Another important instrument is the EXPERT detector unit, which can be easily adapted to FMF2 in the Super-FRS (a basic configuration of the system is essentially ready and was used for pilot experiments at the FRS in FAIR Phase-0, e.g. in experiment G-22-00111 in year 2024) for the exploration of decays and structure of the most exotic nuclides employing the in-flight decay method [3]; these nuclei, located beyond the proton drip line and decaying via (multiple) proton emissions, may exhibit the disappearance of nuclear structure and the transition to amorphous nucleon matter. Other detectors, for instance the “Travelling MUSICs” (for the measurement of nuclear charge and matter radii) or scintillator-based implantation detectors (for the study of fission isomers) are in preparation, and the plans for experiments are presently being discussed in the NUSTAR Collaboration.

Outlook 2025

The main activity in 2025 will be the analysis of the experiments conducted by the Super-FRS Experiment Collaboration in previous years and the publication of the results. Likewise, the focus will be on preparing the FRS pilot experiments of the Super-FRS Experiment Collaboration planned for years 2026/2027, all of which aim to investigate neutron-rich nuclides: direct mass measurements of heavy nuclides to benchmark theoretical models for the r-process calculation in the vicinity of the third abundance maximum, exploration of yields and isotope production in this region, and the use of MNT reactions to produce isotopes beyond ^{238}U. The development of the “Virtual FRS Messhuette” will continue, and remote control of the FRS from the FCC will be implemented. Finally, the ongoing upgrade measures on the FRS will continue during the shutdown. Preparations for a possible new WASA-FRS series of experiments, which could possibly begin in 2028, are to continue.

Acknowledgements

We would like to thank all departments and their staff for their continuous and outstanding support and acknowledge the excellent cooperation, especially the Detector Laboratory, Target Laboratory, IT department, EE department, Beam Diagnostics, ACO, Netzgerätegruppe, Großmontage, PMO-PPL, and - last but not least - the ion-source and accelerator staff and the operators for their excellent support in all experiments: without their expertise and contributions, the above achievements would not have been possible. This is also true for the engineers, technicians, and student trainees of the FRS/Super-FRS Experiments department. The contributions of collaboration partners and guests are acknowledged, too. Finally, the NUSTAR Beam Team has played a key role in preparing and conducting the experiments: the individuals involved are thanked for their personal commitment and contribution; the support provided by many collaboration partners and their contributions to the successful implementation are particularly appreciated.

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Highlight publications of 2024 are indicated in **bold** characters.

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4.3 Nuclear reactions

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

Author: Thomas Aumann

Introduction

The department Nuclear Reactions develops and operates the R^{3}B (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/nucleon. 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, star explosions, and neutron-star mergers by measurements of reactions with short-lived nuclei. A start version of the FAIR R^{3}B experiment has been installed in Cave C at GSI while completion of the detector construction is still ongoing [1]. For the FAIR Phase-0 production beam-time in 2024, the setup has been further completed during 2023 with an upgrade of the CALIFA calorimeter with detectors at the very forward angles, a re-configuration of the silicon vertex tracker including new ALPIDE detectors, as well as a refurbishment of the time-of-flight wall and further construction of NeuLAND. The experiment was devoted to the measurement of short-range correlations as a function of neutron excess for carbon isotopes. In this experiment, the (p,pd) reaction has been employed, a complementary method to the (p,2p) reaction [2] which needs an additional measurement of the recoiling SRC partner nucleon. Here, the correlated n-p pair is knocked out. The trend of the cross section as a function of N-Z provides the information on the isospin dependence of n-p SRC pairs (see also [3] for a complementary method).

Highlights in 2024

Measurement of nuclear interaction cross sections towards neutron-skin thickness determination

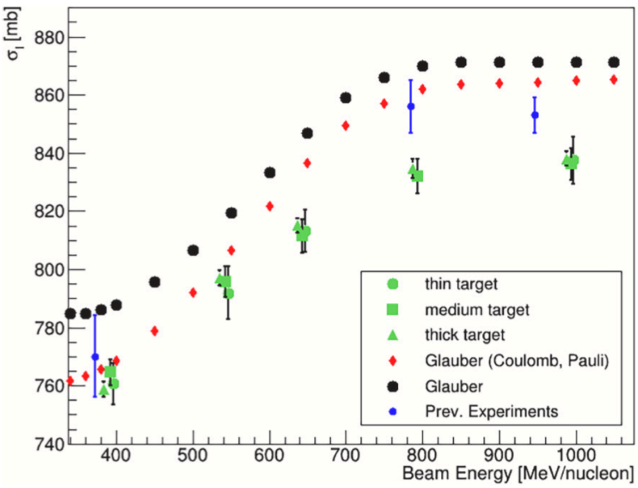

Figure 35**:** Total interaction cross sections of ^{12}C+^{12}C versus beam energy. Experimental data for all target beam combinations (green symbols) are compared with calculations based on a reaction model - with (red symbols) and without in-medium corrections (black symbols) - and data from previous experiments (blue symbols) by Takechi *et al.*, Phys. Rev. C 79 (2009) 061601, Tanihata *et al.*, World Scientific (1990) 477, and Ozawa *et al.*, Nucl. Phys. A 691 (2001) 599. Figure from [4].

The accuracy of reaction theories used to extract properties of exotic nuclei from scattering experiments is often unknown or not quantified, but of utmost importance when, e.g., constraining the equation of state of asymmetric nuclear matter from observables as the neutron-skin thickness. In order to test the Glauber multiple-scattering model, the total interaction cross section of ^{12}C on carbon targets was measured at initial beam energies of 400, 550, 650, 800, and 1000 MeV/nucleon [4]. The measurements were performed during the first experiment of the R^{3}B experiment after the start of FAIR Phase-0 with beam energies of 400, 550, 650, 800, and 1000 MeV/nucleon. The combination of the large-acceptance dipole magnet GLAD and a newly designed and highly efficient Time-of-Flight detector enabled a precise transmission measurement with several target thicknesses for each initial beam energy with an experimental uncertainty of ±0.4%. A comparison with the first-order Glauber reaction model without any adjusted parameter is shown in Figure 35 indicating significant deviations. The inclusion of in-medium effects like Pauli blocking to the first-order Eikonal calculation improves the comparison only slightly. At the higher beam energies, a discrepancy of around 3% is observed. Further developments of the reaction model and additional tests with data are foreseen in order to understand the origin of the deviations. This will serve as a crucial baseline for the model-dependent uncertainty in future fragmentation experiments aiming at extracting the neutron-skin thickness of exotic nuclei from neutron-only removal cross sections.

Magicity versus Superfluidity around ^{28}O viewed from the Study of ^{30}F

The neutron-rich unbound fluorine isotope ^{30}F has been observed for the first time by measuring its neutron decay with the R^{3}B NeuLAND neutron detector at the SAMURAI spectrometer (RIBF, RIKEN) in the quasi-free proton knockout reaction of ^{31}Ne nuclei at 235 MeV/nucleon [5]. The resulting relative-energy spectrum is shown in Figure 36. The spectrum is described by a fit assuming one resonance (full red curve) plus other unresolved resonant contributions (dotted curve). The inset (b) shows the neutron-gated Doppler-corrected γ-ray spectrum of ^{29}F in comparison to a simulated 100% direct γ decay to the known 1080 keV state in ^{29}F (orange line) and to pure background (dashed line), extracted from the reaction ^{29}F(p,2p)^{24}O in which no γ ray is present. The good agreement between the experimental spectrum and background proves that the observed neutron decay occurs to the ground state of ^{29}F. The extracted one-neutron-separation energy of ^{30}F is $S_n = -472(67)$ keV. Figure 37 summarizes experimental and theoretical neutron separation energies for oxygen and fluor isotopes. The absence of a sharp drop in S_n(^{30}F) shows that the “magic” N=20 shell gap is not restored close to ^{28}O, which is in agreement with our shell-model calculations that predict a near degeneracy between the neutron d and fp orbitals, with the $1p_{3/2}$ and $1p_{1/2}$ orbitals becoming more bound than the $0f_{7/2}$ one. This degeneracy and reordering of orbitals have two potential consequences: ^{28}O behaves like a strongly superfluid nucleus with neutron pairs scattering across shells, and both ^{29,31}F appear to be good two-neutron halo-nucleus candidates [6].

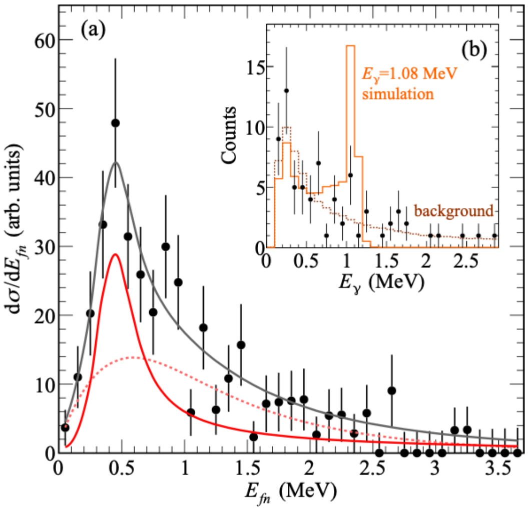

Figure 36: (a) Relative-energy spectrum of ^{30}F reconstructed in the ^{31}Ne(p,2p)^{29}F+n reaction. The data (points with 1σ statistical uncertainty) are corrected for efficiency and acceptance of the neutron detection. The full red curve depicts a fit assuming one resonance, while the dashed curve describes unresolved contributions. The overall gray curve shows the total fit. The inset (b) shows the neutron-gated Doppler-corrected γ-ray spectrum of ^{29}F in comparison to a simulated 100% direct γ decay to the known 1080 keV state in ^{29}F (orange line) and to pure background (dashed line). Extracted from [5].

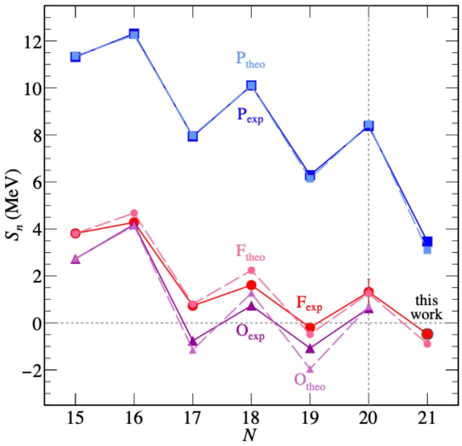

Figure 37: Experimental and theoretical neutron separation energy Sn as a function of neutron number N for fluorine (Z=9), oxygen (Z=8), and phosphorus (Z=15) isotopes. The theoretical results are from shell-model calculations using the SDPF-U-MIX20 interaction. Extracted from [5].

Outlook 2025

During 2024, R^3B and the ASY-EOS collaboration started to prepare and test detectors to be used in 2025 for a new experiment measuring Au+Au heavy-ion collisions. Aim is to derive more stringent constraints on the density dependence of the symmetry energy at supra-saturation densities. The experiment will measure the excitation function of the neutron/proton elliptic-flow ratios in an energy region from 250 to 1000 MeV/nucleon.

Selected publications of 2024

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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 addressed by studying excited states and their decay in the Nuclear Spectroscopy Department (KSP). With comprehensive high-resolution gamma-ray and charged-particle spectroscopy of selected key isotopes, the evolution of the shell structure and exotic nuclear shapes near the limits of nuclear existence and its relevance to the nucleosynthesis of heavy nuclei are being investigated.

The department is continuously developing necessary detectors and instrumentation, as well as the associated experimental methodology, for the spectroscopic investigations. The transfer of technologies derived from the development work is actively pursued for the benefit of society. Many activities are performed together with international partners in the HISPEC/DESPEC, AGATA, MINIBALL, PARIS, and other collaborations, in addition to leading sub-projects within the EURO-LABS consortium (e.g., INTRANS). The department maintains a local group coordinating the activities of the HISPEC/DESPEC collaboration and developing and building the related infrastructure for the experimental campaigns at GSI and FAIR. Two main experimental methods are employed to address the physics goals: the in-beam method where emitted gamma rays and reaction products are measured promptly with the nuclear reactions (HISPEC), and decay method where the properties of each type of the observed decay at rest of the incoming radioactive ion is analyzed (DESPEC). Both types of experiment are performed at GSI/FAIR and in other international facilities such as RIBF, FRIB, LNL and ISOLDE. HISPEC in-beam spectroscopy experiments to be carried out at FAIR are currently in the test phase.

Highlights in 2024

Shape evolution in the rare earth region

The Phase-0 experiment G-22-00100 “Structure of neutron-rich, rare-earth nuclei” was successfully completed in the Spring of 2024. An upgraded version of the DESPEC ‘Hybrid’ gamma-ray array (comprising FATIMA $LaBr_3$ and DEGAS HPGe triple clusters) was used, which provided higher efficiency for gamma-ray detection compared with the configuration used in 2020-2022, with implanted ions and subsequent particle decays observed with the AIDA active-stopper detectors. The setup is illustrated in Figure 38. The experiment studied rare-earth nuclei close to the mid-mid-shell nucleus ^{170}Dy via the world’s first in-flight fragmentation of ^{170}Er ions, providing the means to study the detailed nuclear structure of highly-deformed systems. The data analysis is in an advanced stage, yielding very promising results including the discovery of several new isomers in isotopes with Z=62-67 approaching the N=104 neutron mid-shell. A number of new transitions and excited states have been discovered in the N=102 nucleus ^{168}Dy, as can be seen in Figure 39, leading to an extensive reinterpretation of the low-lying level scheme and indications of new isomeric transitions. A spectrum of gamma rays measured by the FATIMA LaBr3 detectors in coincidence with transitions between the first excited 4^+ and 2^+ states in ^{164}Gd is shown in Figure 40. Further information regarding excited states of nuclei with poorly know (and unknown) level structures has been extracted from the rich data set collected by the DEGAS modules, and work regarding the extraction of nuclear lifetimes using the FATIMA array is underway.

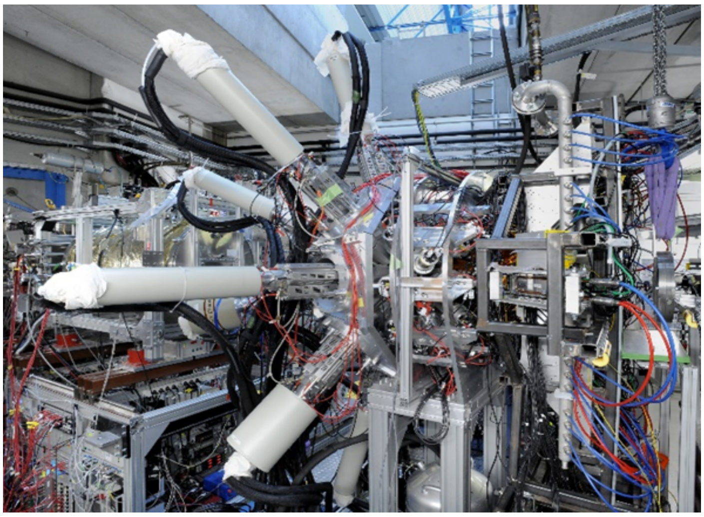

Figure 38: The DESPEC ‘Hybrid’ gamma-ray array in the S4 experimental area.

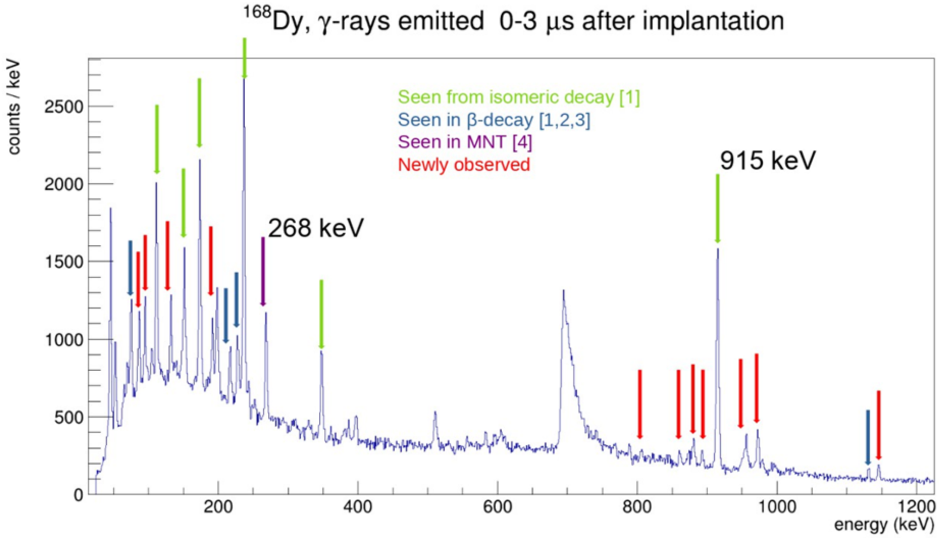

Figure 39: Gamma-ray spectrum measured by the DEGAS array within 3 us of an implanted ^{168}Dy ion. Transitions previously observed are marked in green, blue and purple (reported in [1] G.X. Zhang *et al.* PLB 799, 135036 (2019), [2] M. Asai *et al.* PRC 59, 3060 (1999), [3] G.X. Zhang *et al.* EPJ Web of Conferences 178, 02023 (2018) and [4] P.-A. Söderström *et al.* PRC 81, 034310 (2010)) and new transitions are marked in red.

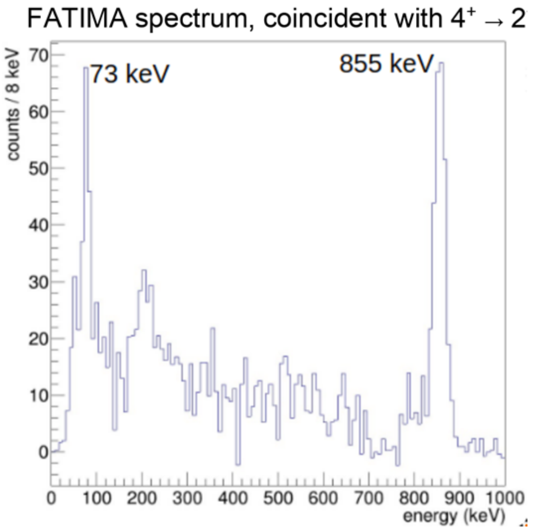

Figure 40: Spectrum measured by the FATIMA LaBr3 array in coincidence with transitions between the first excited 4+ and 2+ states in ^{164}Gd.

Machine learning used in the data analysis

In addition to the conventional analysis techniques that have been used in the last years of the Phase-0 program, new algorithms based on machine-learning approaches have been developed and tested on data collected during DESPEC experiments in 2021. In particular, excellent position resolutions for heavy-ion interactions of σ<1.5 mm have been achieved for the βPlast fast plastic scintillators using kd-tree and ANN methods. An example hit pattern of ^{218}Rn ions stopping inside of the AIDA double-sided strip detector is shown in the right-hand panel of Figure 41; the positions of ^{218}Rn ions stopping inside of a βPlast detector reconstructed using the new methodology are displayed in the left-hand panel of the same Figure. The results are currently being prepared for publication and the techniques are being expanded for use with particle-decay events with the ultimate goal of enabling ion-decay correlations within the plastic material.

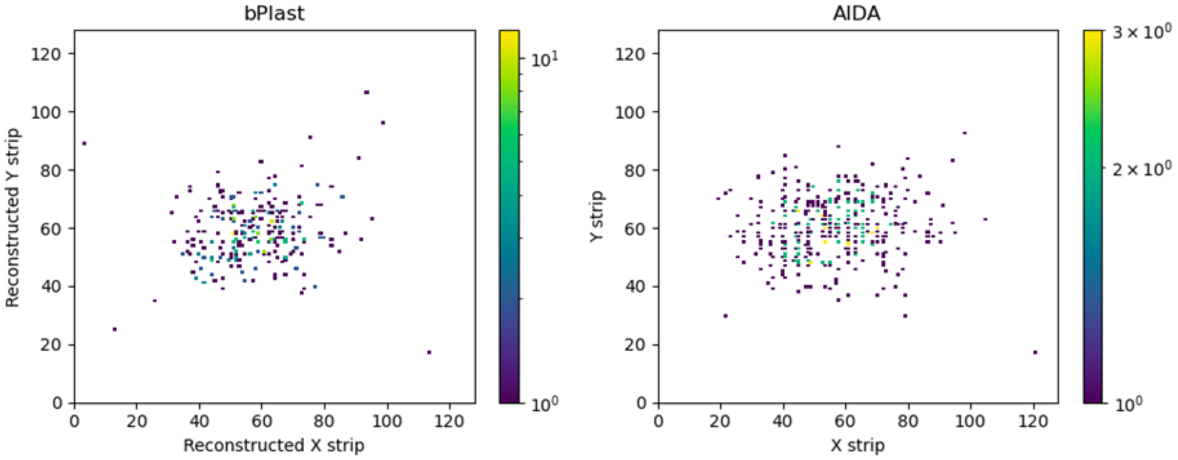

Figure 41: Hit patterns of ^{218}Rn ions stopping inside of a βPlast scintillator detector (left, reconstructed using ML methods) and an AIDA double-sided silicon strip detector (right).

Magicity of ^{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 [1].

In the experiment the ions of interest were produced via fragmentation reactions and implanted into the AIDA active stopper. The excited-state lifetimes below the long-lived isomers were determined using the FATIMA array of $LaBr_3$(Ce) detectors see also [2] [3]).

The newly deduced B(E2) values were compared with shell-model calculations employing different interactions and valence spaces. The results highlight the significance of core-breaking effects and underscore the role of the proton-neutron interaction in shaping the structure of low-lying states—especially the 4$^+$ state, which offers critical insight into the nuclear structure of this region.

While these effects may have limited impact on excitation energies, they appear to significantly influence electromagnetic transition strengths, which are key to achieving a coherent description of these nuclei and their surrounding region.

Ultimately, the proton-neutron component of the effective nuclear interaction emerges as a crucial factor in describing this region of the nuclear chart—relevant for both nuclear structure and astrophysical applications. This is further elaborated in a publication on ^{130}Cd, a two-proton-hole nucleus in ^{132}Sn (see also [4]).

Triaxial shape of neutron-rich Zr nuclei

In a collaborative effort led by our team, we performed the first lifetime measurements of excited states in the neutron-rich isotopes ^{108}Zr and ^{110}Zr using high-resolution in-beam γ-ray spectroscopy at RIKEN's RIBF facility [5]. The extracted lifetimes and newly observed transitions, including low-lying 2$^+$ states, provide compelling evidence for increasing triaxial deformation as the neutron number approaches N=70. These results mark a significant step forward in understanding shape evolution and shell structure beyond the valley of stability. Our findings are compared with state-of-the-art theoretical models, with the symmetry-conserving configuration-mixing approach showing particularly good agreement. This work contributes valuable insight into the structural evolution of heavy Zr isotopes. Further investigations on neighboring isotopes and more detailed theoretical comparisons are currently underway and will be reported in upcoming publications.

Spectroscopic strength in neutron-rich Ca isotopes

The SHARAQ12 experiment was conducted in June 2024 at RIKEN to investigate single-particle states in neutron-rich calcium isotopes. The study focused on probing the spectroscopic strength of neutron states beyond the doubly magic ^{48}Ca via the one-neutron transfer reaction ^{50}Ca(d,p). An energy-degraded secondary beam was produced using the OEDO facility, and missing mass spectroscopy was performed with the TINA detector system. Several states in ^{51}Ca were populated, and preliminary analysis is providing spin-parity assignments and single-particle strength information. Detailed analysis is ongoing, with results to be published in a forthcoming manuscript.

LISA prototype tested

The LISA (Lifetime measurements with Solid Active targets) project, funded by the ERC and led by our group, aims to develop a novel active target system based on layered arrays of single-crystalline diamond detectors. These detectors offer exceptional energy resolution and enable element identification via energy-loss measurements of heavy ions traversing the array. Nucleon knockout reactions can be induced on the carbon nuclei in the diamond itself, making LISA both a detector and a target medium. A first prototype, the LISA 2x2x2 array, was successfully tested in June 2024 at GSI. Installed at the S2 focal plane of the FRS, it was exposed to a cocktail beam of ^{100}Mo fragments at ~300 AMeV. The setup enabled particle identification before and after reactions within the diamond layers. The two-layer system (four detectors per layer) demonstrated excellent energy resolution ($\Delta E/E < 0.6\% \, \sigma$ see Figure 42), sufficient to resolve individual elements even in the uranium region. Energy loss correlations allowed us to identify both the reaction point and the nature of the secondary processes, thus validating the active target concept as shown in Figure 43.

Following the test, significant progress has been made toward the construction of the final 5x5x5 array, including detector procurement, electronics development, and expansion of the DAQ system. In parallel, dedicated simulation and analysis tools have been developed to support future experiments.

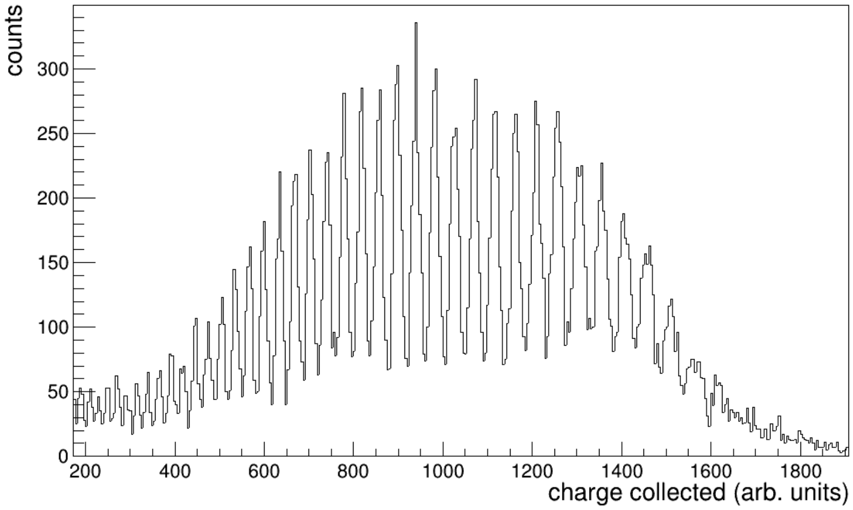

Figure 42: Energy deposit of fission fragments from a U primary beam impinging on a CVD single-crystalline diamond detector at S2.

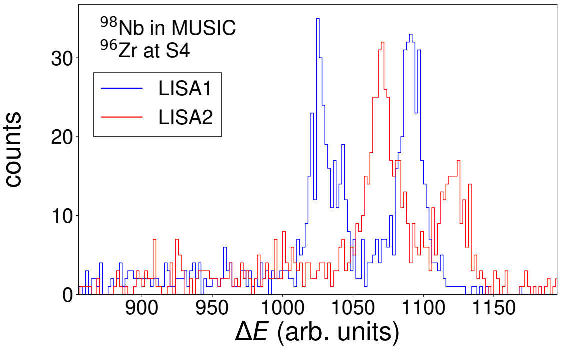

Figure 43: Energy deposit in two layers of diamond detectors for events where a proton removal reaction from ^{98}Nb occurred. The different response of the two layers demonstrates the working principle of the active target.

Fibre Implanter development

In addition to advanced γ- and neutron-detector arrays for decay radiation measurements, an active ion implanter is essential. Its role is to stop isotopes produced by the FRS/Super-FRS, record implantation time and position, detect subsequent β or α decays, and provide coarse energy information to distinguish between decay types.

Currently, DESPEC uses the AIDA implanter, which, however, lacks the <1 ns time resolution required for fast-timing experiments. To address this, the Fibre IMPlanter (FIMP) project has been launched, using scintillating plastic fibres for superior timing. It aims for a voxel size <4 mm, >35% detection efficiency, and the ability to identify and distinguish implantation and decay events.

FIMP consists of orthogonal fibre layers; decay particles (or their secondary electrons) are expected to trigger at least one x and one y fibre, providing full position information. Scintillation light is read out via SiPM arrays mounted along the detector's edges. A prototype ($80 \times 80 \times 11$ mm^3), developed at GSI, was tested at the FRS's S4 focal plane (Figure 44).

In 2024 tests, ^{100}Mo ions were implanted at varying depths using a degrader. Energy deposition in fibres was consistent with Bragg peak behaviour and matched simulations, confirming FIMP's tracking capabilities. At low energies, ions failed to reach the fibre, producing only prompt radiation. Intermediate energies resulted in Bragg peaks, while high energies led to punch-through and reduced energy deposition.

β–γ correlations were observed with ^{98}Nb decays to ^{98}Mo, using four $LaBr_3$ detectors arranged around FIMP. Due to the 51-minute β-decay half-life, direct implant–decay correlations were not seen; this capability will be studied in future tests.

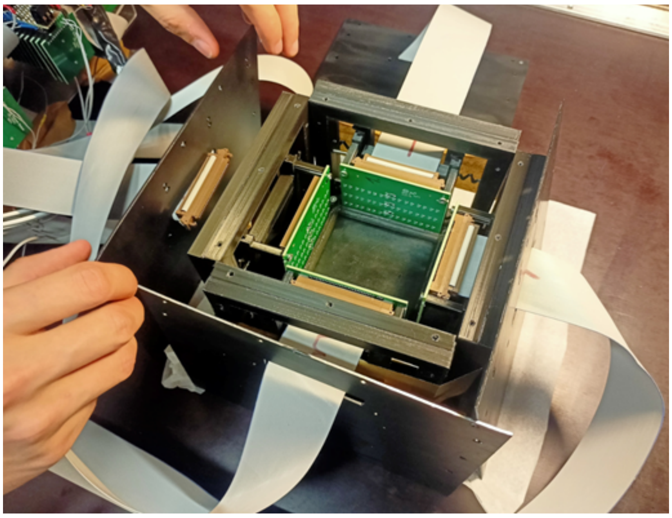

Figure 44: FIMP prototype

Outlook 2025

The experimental work and data analysis from 2024 have been or will be summarized in upcoming publications, several of which appeared in early 2025. A number of new experiments—including dedicated test runs—are planned to prepare the experimental apparatus for the FAIR Early Science program.

With advancements in machine learning techniques, the performance of specific detectors will be further analyzed. Experiments at GSI and other facilities are expected to continue throughout 2025, focusing on the spectroscopy of exotic nuclei.

Selected publications of 2024

[1] 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.

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[3] A. Yaneva *et al.*, “The shape of the tz = +1 nucleus 94Pd and the role of proton-neutron interactions on the structure of its excited states,” *Physics Letters B*, vol. 855, p. 138805, 2024, doi: 10.1016/j.physletb.2024.138805.

[4] A. Jungclaus *et al.*, “Excited-state half-lives in ^{130}Cd and the isospin dependence of effective charges,” *Phys. Rev. Lett.*, vol. 132, p. 222501, May 2024, doi: 10.1103/PhysRevLett.132.222501.

[5] B. Moon *et al.*, “Triaxial deformation of neutron-rich zr nuclei explored by high-resolution in-beam γ-ray spectroscopy,” *Physics Letters B*, vol. 858, p. 139047, 2024, doi: 10.1016/j.physletb.2024.139047.

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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A meta-analysis of nuclear data confirming the existence of a region of increased nuclear stability in the neutron-rich region of the heaviest elements was extended by comparing predictions from a variety of nuclear models. These support the conclusion of the existence of an island of enhanced stability, but make clear that the location of the peak (i.e., the longest-lived nucleus) and the extension of the island are currently not reliably predicted. On the experimental side, the focus in 2024 was on running experiments within the user beamtime served at GSI; 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). Online chemistry studies were performed at NPI CAS Řež (CZ). Furthermore, technical and method developments as well as offline work were performed at GSI and at HIM, for example for applications in laser spectroscopy, where a three-month campaign with the 20-h isotope ^{255}Fm obtained from a 40-d ^{255}Es generator system was employed to support two different studies: on the one hand this allowed complementing laser spectroscopy studies along a long isotopic Fm sequence by this neutron-rich isotope, and on the other hand it enabled fundamental studies in the life sciences [1]. Technical 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.

Synthesis / Nuclear Reactions

The discovery of superheavy elements (SHE) beyond Og (Z=118) remains as a hot topic in the field. Since first attempts to synthesize the elements 119 and 120 in the ^{50}Ti+Bk/Cf reactions at the gas-filled recoil separator TASCA [2], intensive nuclear reaction studies were carried out in collaboration with the Australian National University (ANU), Canberra, Australia, at the Heavy Ion Accelerator Facility of ANU. The projectile ^{50}Ti has been shown to be most promising for the synthesis of elements beyond Og [3], which confirmed the choice for the most promising reaction for the syntheses of 119/120 at TASCA. On the other hand, one of the unresolved issues is the question of how much the cross section will be reduced for ^{50}Ti-induced reactions with deformed targets compared to the known ^{48}Ca reactions. To assist for this problem, the cross sections of three different types of fusion-evaporation reactions with different entrance channel properties were analyzed [4]. For such a compilation, it was necessary to measure the cross sections for ^{50}Ti- and ^{48}Ca induced reactions with deformed targets, which were made at TASCA. The results show the Coulomb force to be the main issue for fusion of the heavy nuclei by substantially increasing the probability of processes preceding fusion, such as quasi-fission. Based on these data and the new systematics, the maximum cross sections for various types of reactions leading to SHN were predicted including the elements 119/120. The recent experimental data for ^{50}Ti+^{244}Pu and ^{54}Cr+^{238}U reactions measured at the Berkeley Gas-filled Separator at LBNL Berkeley, USA and the Dubna Gas-filled Recoil Separator at FLNR, JINR, Dubna, Russia, respectively, are in satisfying agreement with the predictions. A continuation of the started ^{50}Ti+^{249}Cf experiment at TASCA would thus appear sensible.

Nuclear Structure

At TASCA, the nuclear structure research program with the focal plane detection system is ongoing. The search for the extremely short-lived ^{252}Rf was completed in 2024 and the results are now published [5]. This isotope was discovered in the 2n channel of the ^{50}Ti+^{204}Pb reaction by using its long-lived K-isomeric state. The K-isomeric state with a half-life of ≈13 µs enabled the separation of ^{252m}Rf at TASCA during its flight time of about 1 µs. Once implanted, ^{252m}Rf decays via an electromagnetic transition to the ground state; the fast digital electronics was able to register the conversion electrons emitted in this decay. The ground state then undergoes fission with a half-life of ≈60 ns, as deduced from three observed events. This very short value expands the range of half-lives of the known superheavy nuclei by about two orders of magnitude. Our findings set a new benchmark for further exploration of phenomena associated with high-K states and inverted fission-stability in the heaviest nuclei. The electron-capture delayed fission (EDCF) from ^{242}Es has been revisited as well, by producing this nucleus in the ^{48}Ca+^{197}Au reaction. The probability of EDCF was measured directly and with improved statistics [6]. In separate work, the most probable outcome of ternary fission, which is the emission of two heavy fragments and one light charged particle, has been studied. In about 90% of all cases, these are α particles, which are often referred to as long-range alpha (LRA). Such decays have been extensively studied over decades in various heavy fissioning systems and the absolute probability for these processes was found to be about (0.2-0.4) % relative to binary fission. A possible occurrence of this process in superheavy nuclei was considered in recent theoretical work [7]. As a result, it is not excluded that the probabilities of LRA emission are substantial (up to the percent level) in the fission of neutron-deficient heavy and superheavy nuclei.

At SHIPTRAP, a compact buffer-gas cell was designed to enable the use of radioactive recoil sources for offline mass measurements. This mainly concerns heavy nuclides, in particular long-lived actinide isotopes that can be obtained in macroscopic amounts. Such ions can serve as reference ions in online mass measurements and allow us to track changes of the magnetic field of the SHIPTRAP solenoid magnet.

Atomic Physics

The results of laser spectroscopy of 6 on-line produced fermium (Fm, Z=100) isotopes obtained with the RADRIS technique in the FAIR Phase-0 beamtimes in 2020-2022 were evaluated and combined with results on two more fermium isotopes, which were measured off-line at JGU Mainz. The findings along with theoretical calculations were published in 2024 in *Nature* [8]. For the JETRIS setup, where the laser spectroscopy is performed in an effusing gas-jet to improve the spectral resolution, the results from the commissioning beamtime 2022 of the in-gas-jet laser spectroscopy of ^{254}No were finally published in 2024 [9]. The investigation and optimization of the JetRIS setup was continued with the help of collaboration partners from KU Leuven, who contributed to the design and testing of new geometries which led to a promising improvement in the setup off-line efficiency. These improvements will allow probing the 8^- K-isomer in ^{254}No in the next beamtime, which is scheduled for February 2025. Further developments, which took place at the HI Mainz, were performed with a new quadrupole mass spectrometer setup to test and evaluate ionization schemes for later on-line use as well as with the assembly and testing of a new multi-reflection time-of-flight mass spectrometer. The latter will in future extend the capabilities of the group's gas-cell laser spectroscopy program to long-lived nuclides and to nuclides independent of their respective decay mode. For the laser spectroscopy program, a parasitic beamtime with a ^{52}Cr beam was performed in May 2024. Using a ^{107}Ag target the alpha-decaying isotopes ^{155,156}Lu were produced. Lutetium is the iso-electronic homologue of ^{103}Lr and these investigations were planned to benchmark the on-going Lr level search. Unfortunately, this effort was hampered by the fact that mainly the short-lived isomeric state ^{156m}Lu ($T_{1/2}$=198 ms) was produced in this reaction. This short lifetime severely reduces the effective efficiency of the cyclic operation of the in-gas-cell laser spectroscopy with the RADRIS setup. In summary, there was no evidence for laser ionization of lutetium and the data is still under evaluation to understand this behavior. Besides the study of lutetium isotopes, the neutron-deficient isotopes ^{152}Tm and ^{151}Er were investigated by laser spectroscopy for the first time. Here the data is under analysis with the aim to extract nuclear properties on the change of the mean square charge radii.

The collaboration with the Institute of Physics and the Department of Chemistry at JGU Mainz enabled measurements of long-lived actinide isotopes with minuscule sample sizes at the RISIKO mass separator in 2023. The data on ^{254}Cf and on the atomic structure and the hyperfine structure in Fm isotopes was continued to be analyzed. In the latter, additional input was obtained from theoretical atomic calculations by J. Andrews, which helped in understanding the obtained data. At the current stage, the manuscripts are in preparation for publication in 2025.

Chemical Studies

At TASCA, chemistry studies on seaborgium carbonyl complex formation and its reactivity, volatility, and the chemical stability were performed in 2024. The newly tested combined detection system, miniCOMPACT plus COMPACT, allowed for studies of carbonyl complexes with very short-lived isotopes of the superheavy elements, which can be produced in cold-fusion reactions for elements up to ^{107}Bh, with larger production rates than more long-lived isotopes from hot-fusion reactions. To verify this approach, a study with carbonyl complexes of ^{106}Sg was performed at TASCA. The isotope ^{259}Sg was produced via the nuclear reaction ^{52}Cr + ^{208}Pb and pre-separated with TASCA. The Sg recoils were thermalized in a gas mixture of helium and carbon monoxide (CO). More than 60 decay chains originating from ^{259}Sg were registered in the combined detection setup. The Sg-hexacarbonyl complex is formed in the reaction of Sg ions/atoms with CO ligands via a multi-step process. The intermediate reaction products are more reactive and non-volatile, while the final product $Sg(CO)_6$ shows a low interaction strength with a detector surface and adsorbs at a low temperature by physisorption. This study opens the perspective for the first study with carbonyl complexes of Bh, which are yet unknown.

Building on the success of experiments conducted in 2023 in collaboration with the CTU Prague from FAIR aspirant partner Czech Republic, we conducted gas-phase chromatography experiments with gamma-decaying isotopes of Hg (as homolog of Cn), Tl (as homolog of Nh), Po (as homolog of Lv) and At (as homolog of Ts) at NPI CAS Řež (CZ). We employed a versatile setup, designed to study the interaction of Hg, Tl, Po and At with quartz and alpha-Al_2O_3 surfaces of different chemical reactivities. The temperature gradients of the chromatography column ranged from +1000°C to -170°C in thermochromatography studies. The radioisotopes were produced in fusion-evaporation reactions using a 48-MeV ^{3}He-beam, recoiling from the thin target, and thermalized in helium gas. This also served as a carrier gas to transport the volatile At and Hg to the column. The non-volatile Po and Tl isotopes were collected in a Ti, Ta or 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 allowed the determination of the adsorption enthalpy of elemental polonium on quartz and alpha-Al_2O_3 surfaces. Furthermore, elemental At was deposited at temperatures below −60°C on quartz and the complex interaction of Tl, At, and Po compounds with the quartz surface was investigated. Hg was adsorbed on quartz at -130°C, which agrees with known data [10]. The data on Hg, Tl, Po and At are under final analysis.

Chemical Theory Supporting Experimental Work

To assist current gas-phase chemistry experiments on the volatility of At and Po, homologs of Ts and Lv, respectively, and to predict the behaviour of Ts and Lv in future experiments, calculations of formation reaction energies and of adsorption energies, E_{ads}, of these elements and their compounds on gold and hydroxylated quartz surfaces were performed using relativistic periodic density functional theory implemented in the AMS BAND software. For adsorption on gold, for group 15, the compounds under investigation were MH_3 and MO(OH), where M = Bi or Mc, in addition to the previously considered M and MH. For group 16, the MO, MO_2 and MH_2 molecules, where M = Po and Lv, were considered, in addition to the previously considered M and MH.

The results have shown that for group 15, the compounds of Bi and Mc should be rather distinguishable by their adsorption on gold. The sequence in the adsorption strength should be MOOH > M > MH > MH_3, with the Mc species being less strongly adsorbed.

For group 16, the MH_2 compounds of Po and Lv are predicted to be the most volatile over gold among the considered ones. The adsorption temperature should be slightly higher than room temperature, with the adsorption of other compounds occurring at considerably higher temperatures. The PoO, PoH and PoO_2 molecules have nearly identical adsorption energies, making them indistinguishable from each another in experimental settings. This is also the case for the following pairs of molecules: LvO and LvH. Calculated E_{ads} of Po and PoO_2 are in very good agreement with the experimental ΔH_{ads} data for these species confirming the experimental observation stating that *"PoO_2 has a lower affinity for gold compared to polonium"*. The claimed BiPo should have not been observed at slightly lower $-\Delta H_{ads}$ values, however, this supposition should be further checked.

According to the results, in comparison with Po, LvH and LvO should be deposited at lower adsorption temperature, while it should be the other way round for MO_2 and MH_2 compounds. It should be possible to differentiate between Po and Lv by adsorption of these elements and their species on the gold surface.

We have also started the study on adsorption of Po and Lv on hydroxylated quartz surfaces. Considered species are M, MH_2 MO and MO_2. Preliminary results for geminal and vicinal silanols show that the elemental Po should be very volatile over quartz, followed by PoH_2, PoO, and PoO_2. The work is still in progress for Lv and other types of modified quartz surfaces.

Technical developments and key contributions to collaborative work

Further work at HI Mainz and JGU involved the development of laser resonance chromatography (LRC) to investigate the atomic structure of superheavy elements [11]. The LRC apparatus is now in operation. The chromatographic performance of the apparatus was evaluated by analyzing the arrival time distributions (ATDs) of laser ablated Hf^+ ions and the ATD peak separation when comparing Lu^+ and Yb^+ ions in their ground states. A metastable ATD peak was observed for the first time in the Lu^+ arrival time distributions. The LRC was also successfully demonstrated for the first time by initiating the optical $^1S_0$ - $^3P_1$ ground state transition in this ion at about 28,503 cm^{-1}, allowing optical pumping to the metastable $^3D_1$ state. We measured the hyperfine parameters of the $^3P_1$ state in $^{176}Lu^+$ and determined the isotopic shift of the spectral line relative to that of the more abundant $^{175}Lu^+$. To measure the extraction and transmission efficiencies, $^{219}Rn^+$ recoil ions from a ^{223}Ra source, were used. In a typical bunching operation, the overall efficiency of the device was found to be 0.6 %. First commissioning results were published in [12]. Before conducting future studies at in-flight separator facilities, the LRC technique needs to be further optimized to investigate the spectral precision of the method and improve the overall efficiency of the apparatus. Further efforts have been made to investigate the transport properties of heavy metal ions in buffer gas environments. The studies complement the LRC investigations and provide a deeper understanding of the underlying ion-atom interactions. For this purpose, a Cryogenic Ion Mobility Spectrometer (CIMS) was designed, developed, and recently put into operation. Systematic investigations of ion mobility in a wide range of reduced electric fields were carried out for some lanthanides and transition metals, and metastable states were observed for some of them for the first time. This research will be extended to actinide cations in the future.

Also at HI Mainz, the production of tailor-made samples of exotic radionuclides continued to be an important pillar of the SHE Chemistry program. A ^{231}Pa sample was prepared for ISOLDE @ CERN. The sample was used for systematic studies of protactinium molecules (CERN ISOLDE LOI-258). A legacy ^{231}Pa solution from the stocks at Nuclear Chemistry in Mainz was used, which was purified by column chromatography. Subsequently, 1 kBq of the purified solution was dripped into a Ta container provided by CERN, dried, shipped to CERN and used for the production of Pa beams. High-precision mass measurements of artificial ^{163}Ho, and its electron-capture decay daughter ^{163}Dy have been performed at PENTATRAP at MPIK Heidelberg; this work assists the quest for the determination of the mass of the electron neutrino by providing an independent highly precise Q-value of this reaction [13].

The chemical study of elements beyond Mc requires the development of novel techniques to efficiently transfer short-lived (tens of ms) isotopes with half-lives below 100 ms to a gas chromatography detector array. The proposed universal buffer gas stopping cell (UniCell) [14] 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 finalized and the submitted publication is now under review. The advanced ion funnel with an electrode spacing of only ca. 0.1 mm was fabricated by ITE Cracow and arrived at GSI. First electronic circuits to provide the required RF signal to the device were built but do not yet reach the required voltages for operation. To improve the performance, four interfacing printed circuit boards to adapt the 350 electrical contacts of the funnel have been designed in collaboration with the GSI experiment electronics department to match the exact dimensions. After finalizing the electronics and ongoing mechanical works, the commissioning with short-lived alpha-emitting isotopes is planned.

The process of replacing the 40-year-old SHIP magnet power supplies was continued by the procurements of new power supplies for the dipole magnets which were delivered and installed in December 2024. This process was performed together with the GAT and ACO groups of GSI. The functionality of the new power supplies will be finally tested and integrated into the GSI accelerator control system with the aim to use the new power supplies for the beamtime which starts in February 2025. The new dipole power supplies are already within the FESA framework of the new control system of the GSI accelerator chain. After the beamtime the extended break resulting from the ongoing renovation of the experimental hall, will be used to migrate the SHIP control to the new controls system.

Outlook 2025

For the laser spectroscopy program two main beamtimes are scheduled for 2025. The beamtime in February 2025 will be devoted to the in-gas-jet laser ionization with the JETRIS setup. The main goal is the measurement of the Hyperfine structure splitting of the 8^- - K^{π}-isomer in ^{254}No. As the nuclear *g*-factors result from single particle properties, e.g., specific nuclear orbitals, a measurement of the nuclear magnetic dipole moment will enable an assignment of the constituents of the nuclear configuration in this particular isomer. In the second beamtime in June 2025 measurements with the in-gas-cell setup RADRIS will be conducted, Especially the, the long-lived isotope ^{246}Cf , along with other Cf-isotopes will be investigated using a new detector setup consisting of 8 individual detectors to observe the laser excitation signal for different wavelengths on different detectors.

At TASCA, the ^{48}Ca+^{243}Am reaction is planned to be used in Spring/Summer 2025 for studies of ^{288}Mc and its decay products with the new ANSWERS setup.

Building on the success of chemistry studies with seaborgium carbonyl complex, the first study with carbonyl complexes of Bh, which are unknown yet, is proposed as the next chemistry experiment at TASCA. The results of Sg carbonyl study have demonstrated that the combined detection system, miniCOMPACT plus COMPACT, will allow for studies of Bh carbonyl complexes with very short-lived isotope ^{262}Bh, which can be produced in cold fusion reaction ^{55}Mn + ^{208}Pb using the newly developed ^{55}Mn ion beam from the PIG source.

The chemistry studies at NPI CAS Řež will continue to further the understanding of the properties of Hg, Po, and At in contact with quartz surfaces, and the offline studies with ^{216}Po will be extended to cover a wider temperature range. These will be accompanied by theoretical work on the volatility of Po, a homolog of Lv, yielding predictions of the adsorption behavior of these elements and their compounds on surfaces and gold and quartz on the basis of the relativistic periodic DFT calculations.

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Highlight publications of 2024 are indicated in **bold** characters.

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[3] H. M. Albers *et al.*, "Zeptosecond contact times for element z=120 synthesis," *Physics Letters B*, vol. 808, p. 135626, 2020, doi: 10.1016/j.physletb.2020.135626.

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5. Research of the PANDA Departments

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

5.1 Executive summary

Author: Klaus Peters

The PANDA experiment (see Figure 45) 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 (65 Institutes in 18 Countries) 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 connected to the Magnets, the Electromagnetic Calorimeter (EMC), Luminosity Detector (LMD), the Cluster-Jet Target and the experiment infrastructure. This is accompanied by Phase-0 activities involving PANDA hardware like PANDA@HADES, PANDA@MAMI, PANDA@ELSA in Darmstadt, Mainz and Bonn respectively and cooperation for the GlueX-DIRC at Jefferson Lab (Newport News, USA) as well as data analysis at GlueX and BESIII at IHEP (Beijing, VR China) [1]. To accomplish the goals, the department teams up inside GSI with the Electronics Lab, Detector Lab and the sections EMP and SPECF of the Helmholtz Institute Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

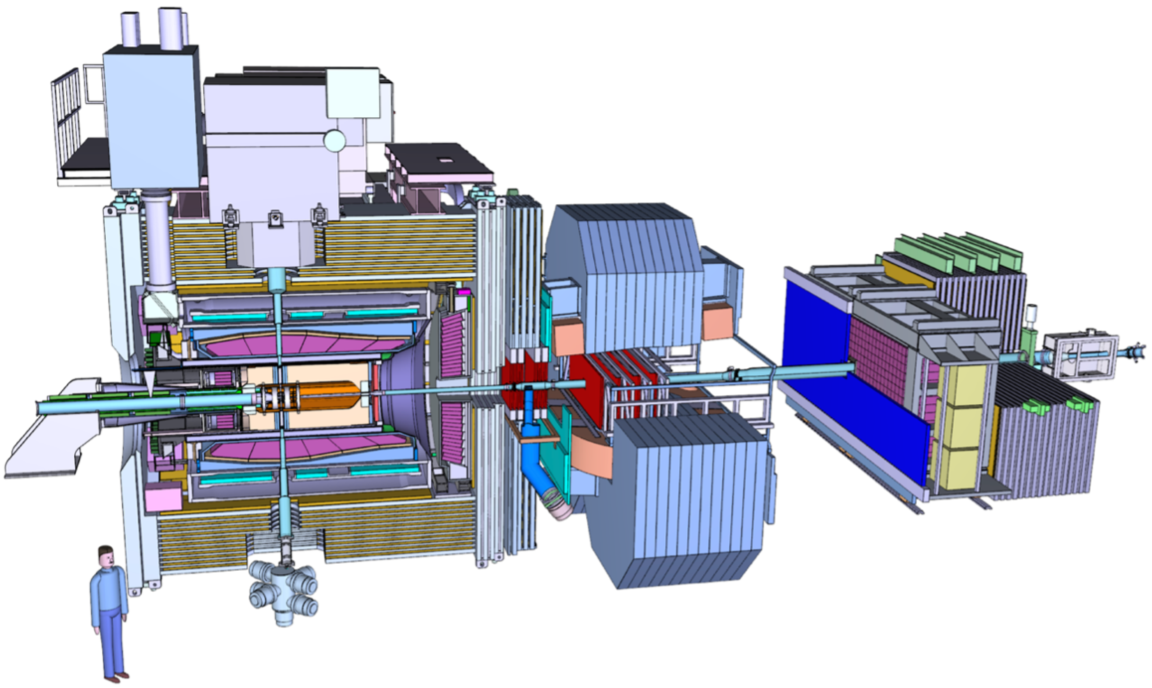

Figure 45: The PANDA Detector (Illustration by J. Lühning, GSI)

Selected publications of 2024

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5.2 Hadron spectroscopy

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

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

Highlights in 2024

PANDA Coordination

PANDA Magnet

The construction of the PANDA solenoid by industry – a necessary consequence of the cancellation of the contract with BINP/Russia - requires having an aluminum stabilised superconducting cable. Samples (see Figure 46) of the currently only available cable from Wuxi Toly Electrical in China were obtained in spring 2024 and were tested at University of Twente, NL end of 2024, to characterize the suitability of the cable for PANDA. The tests comprised transformer tests of the critical currents of individual strands and the complete cable, performed at 4.2 K with magnetic fields from 3 T to 9 T. Peeling tests showed a good intermetallic bond between aluminum and copper and shear tests demonstrated a strength of up to 22.5 MPa. Investigations with electron microscope revealed the placement of the Rutherford cable within the extruded aluminum. In addition, the Residual Resistance Ratio (RRR) was determined from measurements at 4.2 K and room temperature. The tests showed that the conductor is well suited for the PANDA solenoid.

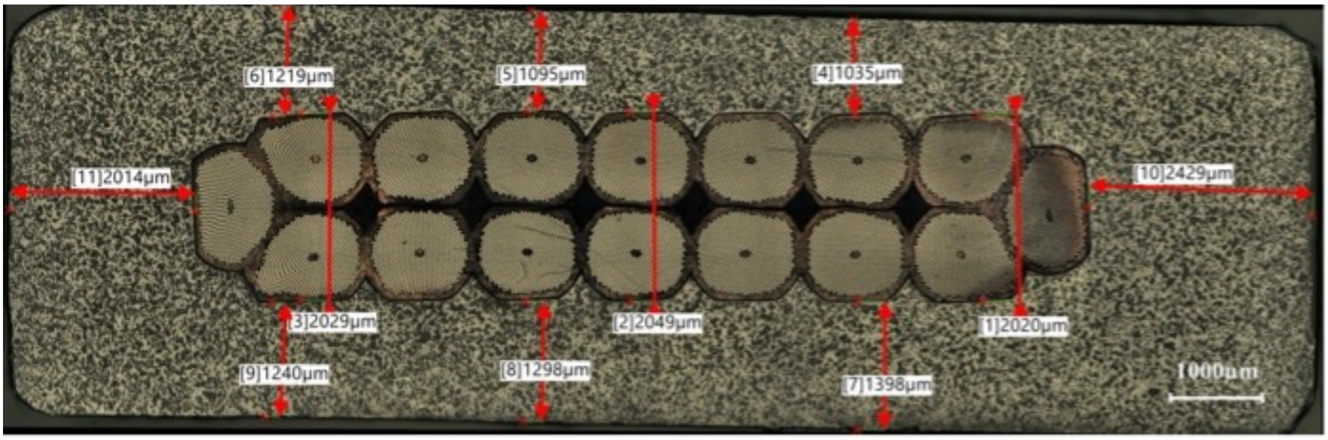


Figure 46: Electron microscope picture of the cross section of the tested cable.

As alternative option the use of the existing superconducting coil of ZEUS/HERA available at DESY, was studied with simulations. Regarding the tracking a 2-3 times worse momentum resolution was observed in the central tracker. Also, the ZEUS magnetic field falls off steeper than in the original PANDA solenoid making the resolution for low angle tracks much worse. Simulations of a Barrel EMC composed of 12 of the original EMC slices showed significant acceptance loss due to the tilted arrangement due to the smaller radius. For these reasons, the ZEUS solenoid is not considered a suitable replacement of the PANDA solenoid, at least not for most of the physics topics.

PANDA Barrel EMC – Slice-0

The slice-0 is the first slice to be completely assembled and tested under real operational conditions at -25°C. The readout is based on the APFEL ASIC designed at GSI, which must be mounted on a flex-PCB cable, as required for the transition from the cold to the warm volume of the slice. To complete a set of 1000 pcs, needed for slice-0, we started using the fully automated mounting device at GSI. We have re-designed the soldering masks such that to maximize the yield and minimize post-mounting works. A proto-series of 45 pcs have been automatically mounted at GSI and tested at JLU Giessen by hand, achieving the desired yield. For the full series (1000 pcs) we have designed a test station capable to automatically test multiple pcs and storing the test results for further QA purposes. All electronics components from JLU Giessen are at GSI and the test station is being build.

PANDA Satellites

After the successful transfer of the PANDA Forward Endcap EMC to Bonn, further design work on the mechanical structure for the insertion, alignment, and support of the detector at the location at ELSA was contributed by GSI. Contracting of components will take place in 2025 when the project received its full approval.

A further preparatory project for PANDA is the continuation of measurements of elastic scattering of protons with the KOALA setup, that started at COSY in Jülich. The measurement serves as input for the determination of the luminosity from elastic scattering of antiprotons off protons. The setup at Jülich consisted of the PANDA Cluster jet target, a scintillator detector for the recoil proton and a prototype of the luminosity detector for the scattered beam proton. In this context the PANDA cluster jet target and the PANDA luminosity detector will be transferred to Cave C at GSI during 2026/27. Preparations and design work for this setup were started in late 2024. The layout of the cave shall accommodate both the KOALA setup as well as commissioning setups of the CALIFA and ACTAF systems from NUSTAR to be tested still in Cave C before moving to the High Energy Cave of FAIR. In this intermediate program also joint physics opportunities in cooperation between PANDA and NUSTAR are in consideration. Figure 47 shows a preliminary CAD layout of the Cave C area implementing the KOALA, ACTAF and CALIFA setups.

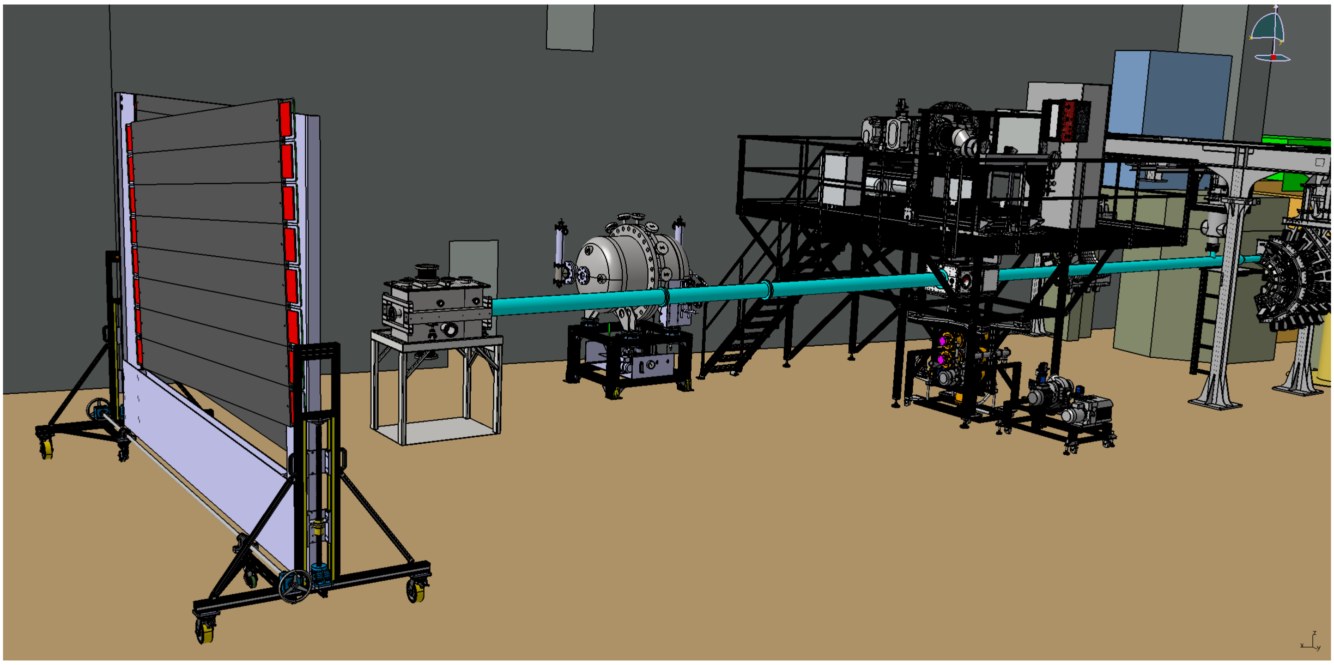


Figure 47: Preliminary setup of Cave C with KOALA, ACTAF and CALIFA.

EuCAIF

PANDA is a founding member of EuCAIF, an European initiative for advancing the use of Artificial Intelligence (AI) in Fundamental Physics which includes particle physics, astroparticle physics, nuclear physics, gravitational wave physics, cosmology, theoretical physics as well as simulation and computational infrastructure and we contributed to the first “European AI for Fundamental Physics Conference” (EuCAIFCon 2024) held in Amsterdam.

PANDA Outer Tracker

Since the arrival of the Outer Tracker at GSI we have continuously prepared for its readiness to operate in PANDA and possibly at various beamlines at GSI/FAIR and elsewhere.

The PANDA readout boards developed at GSI/EEL are capable to interface the original AISCs of LHCb with the PANDA DAQ, as shown with extensive tests in the lab and also on an actual Outer Tracker module under operational conditions. This has initiated an effort to interface the PANDA readout boards with the CBM DAQ in preparation to operating an Outer Tracker module under beam conditions with mCBM.

We have completed the design of the automated remote monitoring system for multiple sensor units. A prototype of such sensor network is in operation in the Outer Tracker distributed within the transport frame and in the storage Hall BE42, and also implemented in the Detector Lab by a student in the GSI international summer school in summer 2024.

In order to remove a complete C-frame out of the transport frame with minimal means of crane usage, we have devised a new procedure which ensures the detector and operators safety and also designed a set of trolleys dedicated to support and move a C-frame safely into Cave-C, for beam times at GSI.

In addition to PANDA, further use cases of the Outer Tracker in CBM are being considered by a dedicated Task Force with members from both collaborations, led by A. Belias of the PANDA TC-Team. In regular meetings the Task Force examines the feasibility of using OT straw modules in the CBM MUCH system, based on simulations and previous operational experiences of the OT at LHC.

Software and Analysis

PANDA Straw Tube Tracker Software

In order to efficiently study different geometries of the Straw Tube Tracker (STT) being the central tracking detector of PANDA, the code within the experiment software package PandaROOT to simulate and reconstruct this detector component was completely refactored and reimplemented. The simulation and reconstruction stage now can deal with any kind of geometry design, and all hard-wired parts in the algorithms have been replaced. The digitization and reconstruction stage both now use a parametrized model of the electron avalanche in the straw tubes and thus offer a more realistic mapping between drift time and wire distance, that can even be tuned by external parameters. A newly implemented software tool allows for generating an ASCII geometry file of the STT in the .geo format together with an additional data file containing information like neighborhood relations between the straw tubes for tracking and clusterisation. The geometry generation can be controlled by a comprehensive set of parameters like straw size, length and pitch angle, number and configuration of straight and skewed layers, overall detector size and others. In addition, this tool allows for visual interactive inspection and scrutiny of the generated geometry.

RootAnaTools - A ROOT Tools Collection

In data analysis connected to hadron and particle physics certain tasks have to be performed over and over again. While the ROOT analysis framework provides a huge bunch of functionalities in particular for data fitting and visualization, it can be cumbersome and lengthy to properly configure all properties in a consistent and efficient way. To overcome this issue, a collection of interlinked tools has been compiled, that allows to generate, configure, draw and fit various ROOT objects in a very compact and consistent way. The central part of the tool set is the string-based parameter manager 'TParMap', that is able to parse parameter strings, where the named (vectors of) parameters can be accessed as integer, float or string type. Since each parameter can specify a recipient object by definition of a so-called 'scope', the given parameter string can be safely transferred through the object hierarchy to allow for a very compact and interactive control. The parameter parser also provides functionality to conveniently handle default parameter settings and can help to detect mistakes/typos of specified parameter names.

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 three datasets collected with the GlueX detector in 2017 and 2018 has been refined and completed. The differential production cross section $d\sigma/dM_{\varphi\pi\pi}$ of the above channel as a function of the invariant $\varphi\pi^+\pi^-$ mass has been carried out. Fits to this distribution reveal two structures at about $m = 1820$ MeV/c^2 and $m = 2240$ MeV/c^2. The lower mass structure could possibly be identified with the $\varphi_3(1850)$, that, however, has not yet been seen in this decay channel. The higher mass structure does not match the shape of the φ(2170) but can be described well with resonance parameters of a signal previously found by BESIII in the reaction $e^+e^- \rightarrow K^+K^-$. The two signals have about 3σ and 5σ statistical significance, respectively. The paper draft has been reviewed and is aimed to be published in PRL soon.

FAIR Phase-0: Analysis of BESIII Data

Within the scope of a PhD thesis, the search for possible resonances in the energy-dependent cross section of the reaction $e^+e^- \rightarrow \eta_c\gamma$, based on data taken by BESIII, has been started. The motivation for this analysis is the search for exotic resonances like the Y(4230) in the energy dependent cross-section, where the detection of a radiative decay to the charmonium ground state will be an important input to the classification and theoretical understanding of this or other such resonances. The η_c is being reconstructed in 14 different hadronic decay channels, and roughly 25% of the XYZ data taken by BESIII have been analyzed so far. Simulated signal Monte Carlo data has already been produced for all the channels at a subset of beam energies, which will be completed for all energies in the near future.

Outlook 2025

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 2032 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).

5.3 PANDA Detectors

Head: Dr. Jochen Schwiening (GSI)

Authors: Dr. Roman Dzhygadlo (GSI), Andreas Gerhardt (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 2024

The PANDA Barrel DIRC, a German in-kind contribution to FAIR, will 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 155 MCP-PMTs by Photonis Netherlands BV, followed by a detailed characterization of the sensor quality at FAU Erlangen, is underway.

The construction of the Cosmic Ray Telescope (CRT) facility at Stony Brook University (SBU), USA, made significant progress with the deliveries of the PICOSEC Micromegas detector prototype, expected to provide an event timing precision of better than 30 ps, and a CO_2 Cherenkov threshold counter, which will tag particles with a momentum larger than 3.5 GeV/c. These systems, combined with three layers of μ-RWELL tracking detectors, will form the test bench for the ePIC hpDIRC setup, based on the PANDA Barrel DIRC optics, sensors, and electronics on loan from GSI, to validate the performance of the hpDIRC design with upgraded components. [1]

LHCb TORCH R&D

In the summer of 2024, the GSI DIRC group joined the LHCb collaboration at CERN as Technical Associate Member to participate in the R&D for the TORCH system. This DIRC-based time-of-flight detector is part of the proposed upgrade of the LHCb detector, foreseen for the high-luminosity phase of the LHC. TORCH aims to provide particle identification of hadrons in the 2—20 GeV/c momentum range, exploiting the prompt production of Cherenkov photons in an array of fused-silica plates. By joining the TORCH project, GSI is able to capitalize on the many synergies between the TORCH and the PANDA DIRC detectors and gains access to expertise in optical bonding, mechanical design, and running DIRC simulation and reconstruction code on hardware accelerators, such as IPUs or GPUs.

During the fall of 2024, the decision was made to integrate the TORCH detector into the mechanical structure of the LHCb RICH2 detector. This imposes severe space limitations, requiring a redesign of the focusing optics. Detailed Geant4 simulations are used to minimize the space requirements for the TORCH focusing block. The same simulations are used to optimize the placement of the MCP-PMTs (Figure 48) on the focusing block, validate the sensor response to the new laser pulser calibration system, and study the expected performance of the prototype setup during the planned test beam at CERN in the summer of 2025.

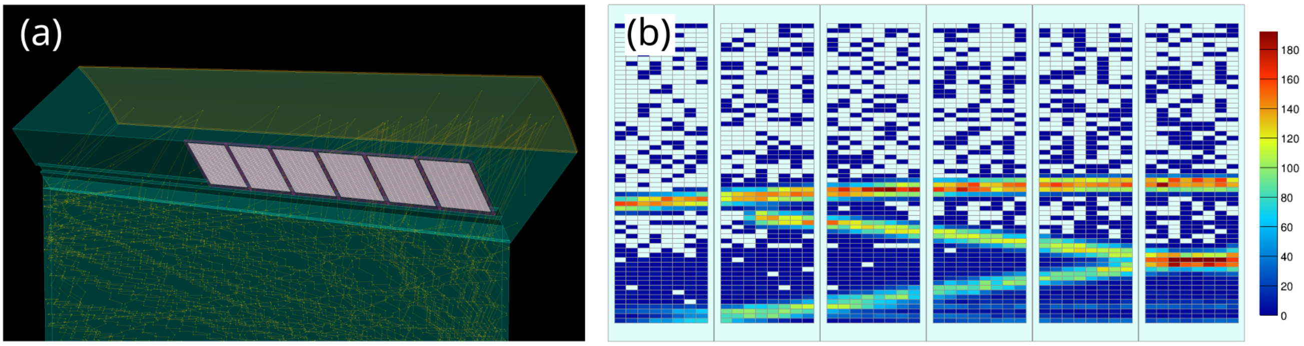


Figure 48: Geant4 simulation of the TORCH prototype (a) and expected accumulated hit pattern from 5000 pions at 8 GeV/c beam momentum (b).

PANDA Barrel DIRC Mechanical Integration

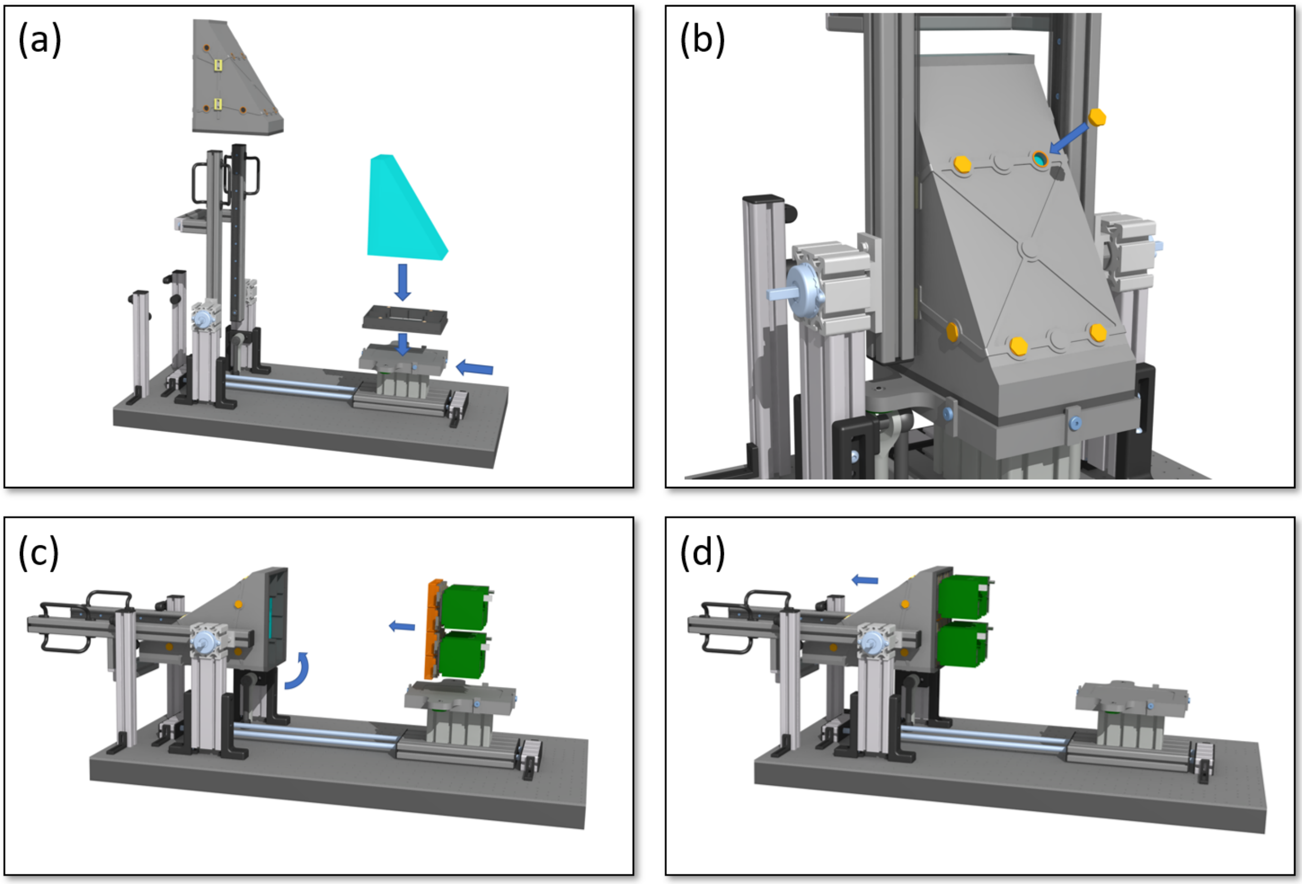


Figure 49: CAD visualization of the fixture and assembly process for the PANDA Barrel DIRC readout box.

One of the main components of the PANDA Barrel DIRC detector are the 16 readout modules that are optically connected to the 16 bar boxes, containing the radiator bars and lenses. Each of these modules comprises a fused silica prism that must be optically coupled to 8 MCP-PMTs in a light-tight housing, using silicone cookies. An assembly setup, shown in Figure 49 was developed to assemble the first prototype module.

The prism is placed on a mounting plate (Figure 49a) on pins in a grid and aligned to within ± 2 mm of the nominal position. Since this is done manually, good accessibility must be guaranteed from all sides. Therefore, the mounting plate is placed on a fully machined and preassembled slide, which can be precisely moved to the next mounting position using ball bearings and guide bushings. Only then is the cover lowered onto the prism and screwed to the grid. A total of 14 special PEEK pins are screwed into the sides of the cover (Figure 49b), thereby determining the final position of the prism within the housing. To install the optical cookies and the 8 MCP-PMTs, the mounting slide is moved back and the box rotated by 90 degrees (Figure 49c). The precise rotary bearing is equipped with a rotary damper to ensure gentle and controlled rotary motion. After placing the optical cookies on the sensors, the DiRICH backplane with the 8 MCP-PMTs can be installed. Fixing brackets provide a light-tight seal on the rear of the backplane. The fully assembled module can now be slid out of the mounting guide (Figure 49d).

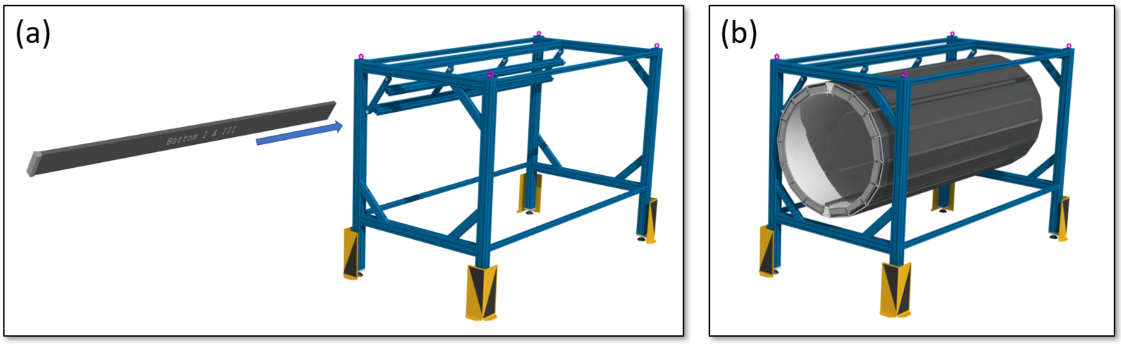


Figure 50: CAD visualization of the mock-up for the installation of bar boxes into PANDA.

The radiators of the PANDA Barrel DIRC detector are housed in 16 modules (3 fused silica bars per module) with a length of 2450 mm, arranged in a barrel with a diameter of 1076 mm. They are held in a support frame, which also serves to suspend additional internal detectors (Straw Tube Tracker, Micro Vertex Detector). In order to test key features before the design is finalized, a mock-up setup has been designed. An aluminum frame (Figure 50a) will accommodate the full-size barrel. Initial tests will start by of inserting a single prototype bar-box module into a frame slot. The slot is initially simulated using aluminum rails to test various insertion systems (slide strips, ball bearings, roller elements). The bar-box module is docked to the slot in a roller conveyor and then inserted. This also tests the handling and installation sequence of such a process. Later, the entire finished frame can be tested on its original suspension points in the aluminum frame (Figure 50b).

Outlook 2025

The series production of PANDA Barrel DIRC MCP-PMTs and the quality assurance measurements of these sensors at the FAU Erlangen will come to a conclusion in the fall of 2025. The Barrel DIRC assembly and installation tests, using the first prototypes of the bar box and readout box components, will continue in 2025, with the goal of finalizing the mechanical design in 2026. The scoping process for the LHCb Upgrade 2 will be completed in 2025 and the first full-size prototype of the TORCH detector will be tested with particle beams at the CERN PS in the summer of 2025. The GlueX experiment will take data in 2025 with the DIRC system installed, providing a new high-statistics data sample for the validation of the PANDA Barrel DIRC simulation and reconstruction algorithm as part of the FAIR Phase-0 effort.

Selected publications of 2024

[1] G. Kalicy, “The high-performance DIRC for the ePIC detector at the EIC,” *Nucl. Instrum. Meth. A*, vol. 1062, p. 169168, 2024, doi: 10.1016/j.nima.2024.169168.

6. FFN (FAIR Forschung NRW)

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

6.1 Executive summary

Author: James Ritman

The department FFN combines the scientific expertise that was previously located at the Forschungszentrum Jülich, mostly working at the Cooler Synchrotron COSY, and has now been transferred to GSI to primarily strengthen its contributions towards FAIR. The department maintains strong connections with several universities (primarily) in the state of NRW, where significant personal and activities are located. In the field of nuclear and hadronic physics, the department is now making significant instrumental and programmatic contributions to the HADES and CBM experiments as detailed below. Furthermore, the expertise acquired in precision physics with polarized beams has been directed to completing studies in preparation of a storage ring measurement of the deuteron's static electric dipole moment, and is in the process of being redirected towards precision storage ring measurements at ESR and within NUSTAR. The department's activities in neutrino physics are led by a group leader with a joint professorship with the JG-Univ. Mainz and is making major contributions towards the JUNO experiment. The department also pursues a couple opportunistic activities that are synergetic to the main activities already mentioned. For near future we look forward to be able to hire group leaders with joint university appointments for the storage ring activities (Univ. Köln), hadron physics (Ruhr-Univ. Bochum), and precision physics (Univ. Bonn).

6.2 HADES

Authors : A. Foda (GSI), V. Kladov (RUB and 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)

Highlights in 2024

Members of this department are extracting hadron-physics observables from exclusively reconstructed reactions in proton-proton and pion-proton collisions. This includes analyzing HADES data collected in 2022 with a FAIR Phase-0 proton beam of T=4.5 GeV and planning upcoming experiments using secondary pion beams: Significant progress has been made in analyzing the **elastic proton-proton scattering** process to determine the total integrated luminosity (L). A preliminary value of L = (5.86±0.09) pb^{-1}. The differential cross-section was obtained and is well described by a function of the form $d\sigma/dt = Ae^{-B|t|}$. Preliminary results for the optical point A = (93.36±0.12) mb/(GeV/c)^2 and nuclear slope parameter B = (8.23±0.01) (GeV/c)$^{-2}$ are in agreement with existing data at other beam energies. **Single-pion production** is investigated in the exclusive reaction $p + p \to p + n + \pi^+$ with the objective to extract information on the intermediate Δ and N* resonance formation. Exploiting a missing-neutron mass analysis, a high statistics sample with excellent signal-to-background of the reaction of interest has been obtained. The Dalitz plot reveals a rich spectrum of intermediate N* and Δ resonances. Investigations are ongoing to compare the data to a recently developed coupled-channel framework based on the Juelich-Bonn potential. A central theme of our research portfolio is to provide information on the **hyperon production** mechanisms in proton-proton collisions. Thus, the exclusive reaction process $p + p \to p + \Lambda + K_S + \pi^+$ with $\Lambda \to p + \pi^-$ and $K_S \to \pi^+\pi^-$ has been studied with a worldwide record in statistical significance by using high-level particle identification techniques and exploiting kinematic fitting tools. The data reveal clear contributions of intermediate Δ++, Σ^* (1385) and K^* (892) excitations. The data are well described by a combined fit of the data based on an incoherent sum of these excitations together with a 4-body phase space distribution. In addition to studies of hyperon production with single strangeness, a study is ongoing to extract the production yield of **hyperons with double strangeness**, *i.e.,* near-threshold production of Ξ^- hyperons. An upper limit of 75 nb for the inclusive Ξ^- production is determined, implying that multi-step production contributes to the excess observed in heavy ion data. The inclusive production of Σ^-(1385), which decays into the same final state is used as a control and is observed with high statistics. The analysis of the **hidden-strangeness** process, $pp \to ppK^+K^-$, progressed with significant improvements in neural network-based hadron particle identification. The experimental misidentification rate of pions was reduced to below 3%, while the kaon identification efficiency exceeded 80%. Detector resolutions for the kinematic refit were finalized through optimized multidimensional binning, leading to an improved signal-to-background ratio of approximately 25. Differential and total cross section values for the reaction were obtained, and preliminary investigations into the final-state interactions between different particles and the measurements of spin-density matrix elements (SDMEs) for ϕ meson spin alignment were conducted. The upcoming **pion-beam at HADES** offers significant advantages over proton induced reactions and complements photoinduced research to explore baryonic resonances. Using Partial Wave Analysis techniques (PWA), the coupling of these resonances to various final states is investigated. Detailed PWA studies of pion induced reactions on protons are expected to provide valuable insights into the complex couplings of baryonic resonances to ρN and ωN final states. These studies are crucial for understanding the ρ meson's behavior in heavy-ion collisions and the role of intermediate vector mesons in dilepton production. We are developing a modular software package to enable precise mapping of resonance regions and extraction of resonance parameters, such as mass, width, and contributions to various channels. The new PWA framework is being confirmed with a reanalysis of the 2014 pion beam data, and with a sensitivity study of the N(1720) double resonance. As part of the NRW-FAIR network activities, techniques for **real-time calibration using Machine Learning** are being explored to automate sensor calibration during data acquisition, addressing challenges associated with deploying free-streaming data acquisition systems in future FAIR experiments. A neural network-based approach to predict calibration parameters in real time using continuously available environmental data is tested with the Multi Drift Chambers (MDC) of HADES. A model based on a Long Short-Term Memory (LSTM) architecture with Graph Convolutions to account for correlations between different channels has been developed. Improved offline calibration methods were implemented to provide reliable target values for training. The neural network was optimized to mitigate overfitting and can predict HADES MDC gain calibration factors stably over several weeks without retraining. The offline calibration framework was adapted to process cosmic data, which is crucial to determine high-voltage dependencies in the calibration constants.

Outlook 2025

- Publication of elastic proton-proton scattering results. Completion of analysis of hyperon production channels.
- Preparations upcoming experiments with pion beams and HADES.
- Write-up of a white paper presenting the successor program with proton and pion beams with FAIR setups, e.g., CBM.

6.3 CBM

Authors : F. Goldenbaum (FZJ and BU-Wuppertal), D. Grzonka (GSI and FZJ), 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), P. Wintz (FZJ) and R. Yang (BU-Wuppertal)

Highlights in 2024

The neutron detector **NCAL** is considered to enhance the forward spectator detector (FSD) to improve the determination of the reaction plane and collision centrality for heavy ion reactions and to measure forward going neutrons in proton/deuteron reactions. The NCAL will consist of 86 hexagonal 45 cm long plastic scintillator modules covering a total area of about 1.4 m^2 with a neutron detection efficiency of 40 - 50%. Two test units with seven modules each have been prepared for performance studies to find optimal settings to cover the full dynamic range. One NCAL test unit was installed at the mCBM detection system and used in several mCBM beam times. In the most recent data taking an arrangement of 9 FSD-modules each containing a (3 cm)^3 plastic scintillator were placed in front of the NCAL unit. The data are being analyzed and compared with GEANT4 simulation studies. A second NCAL test unit was used for further tests with cosmics, radioactive sources and for an investigation with a neutron beam at the cyclotron of the Nuclear Research Institute in Rez. The neutron beam, produced by bombarding a Li-target with protons, has a neutron energy around 32 MeV and the intensity could be adjusted to a sufficient low level that single neutrons could be separately detected. The data are currently being analyzed and will be compared to simulation results. A crucial component of CBM is the Transition Radiation Detector **TRD**, which identifies electrons above 1 GeV/c. An efficiency > 90% will be achieved by using a gas mixture of xenon and CO2. Since xenon is expensive, a critical part of the TRD is its gas system, which must ensure among other aspects that the gas overpressure in the TRD must be precisely controlled and kept within a range of about 0.2 - 0.6 mbar. The full system will be based on a prototype of the gas system developed at the Univ. of Münster.

Outlook 2025

- The NCAL will be further characterized using the fully tracked data collected during the mCBM beam times, and the neutron data collected at Rez.
- The TRD gas system prototype will be relocated to the Forschungszentrum Jülich, where further development work on the system will continue.

6.4 Neutrino physics

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

Highlights in 2024

The neutrino group has been actively contributing to the Jiangmen Underground Neutrino Observatory (JUNO) multi-kiloton neutrino experiment in China. The group has conducted extensive studies to evaluate JUNO's sensitivity to various physics goals, including the determination of neutrino mass ordering (NMO) and measurement of neutrinos from natural sources such as the Sun, the atmosphere, and the Earth's interior (geo-neutrinos). For solar neutrino studies, the group is exploring the potential of a novel method, Correlated and Integrated Directionality, to determine the precision of solar neutrino measurements achievable at JUNO. To enhance JUNO's overall sensitivity to the NMO, the group is also investigating the potential of using atmospheric neutrinos for NMO determination. In the field of geo-neutrino research, the group is analyzing JUNO's sensitivity to geo-neutrino detection, with a focus on measuring the total geo-neutrino flux, distinguishing the independent contributions from heat-producing elements (uranium and thorium), and identifying the contribution from the Earth's mantle. Additionally, the group has studied a key background source for antineutrino detection, the so-called ($\boldsymbol{\alpha}$, n) background, estimating both its expected interaction rate and its energy spectrum. The group has been actively involved on-site by making contributions to commissioning tasks, including characterizing the detector response, estimating background levels, and implementing data quality monitoring from the early stages of data collection. One important highlight is that JUNO has now started fill the detector with water.

Outlook 2025

- Publication of a JUNO collaboration paper about the (α n) background.
- Completion of a JUNO collaboration paper about sensitivity to geoneutrinos.
- Completion of analysis and JUNO collaboration paper about the sensitivity to solar neutrinos with CID directional analysis.
- JUNO detector is planned to be fully filled with liquid scintillator.

6.5 Polarized atomic beams

Authors: R. W. Engels (FZJ), L. Capelan (HHU), N. Faatz (GSI and RWTH), C. Kannis (HHU), J. Salmann (GSI and RWTH) and S. Pütz (GSI)

Highlights in 2024

Investigations of the spin interactions of a beam of metastable hydrogen/deuterium atoms with magnetic field gradients were continued at energies in the range of a few keV. In contrast to the previously dominant longitudinal magnetic fields, the focus in 2024 was on transverse fields generated by two pairs of coils with opposite field directions. Motion-induced transitions occurred at neV energies between the hyperfine structure states. This understanding now allows for, *e.g.,* an improved transfer of the electron polarization of atoms or the polarization of the rotation of an H_2/D_2 molecule to the nucleus. This opens up completely new possibilities for polarization generation for various applications, *e.g.,* in "polarized nuclear fusion". Based on these results, a new generation of spin filters was developed, which will allow the occupation numbers of all four hyperfine structure states of metastable hydrogen to be determined. This is necessary, for example, for the BoB experiment on bound neutron decay. A transfer of this technique to polarized ^{3}He ions also would allow the polarization of such beams to be measured analogous to the Lamb-shift polarimeter. The possible use of a Lamb-shift polarimeter also for pulsed H^-/D^- beams was further optimized and could now be carried out on corresponding ion sources at accelerators.

Outlook 2025

The SPIN@LHCb collaboration will use a nuclear spin-polarized target at the LHC. For this a T-shaped storage cell is to be fed with polarized hydrogen atoms from a polarized atomic beam source (ABS), which will then serve as a target for nuclear reactions [1]. The ABS previously used in the PAX@COSY experiment was relocated to the INFN in Ferrara, where it will be used in a precursor experiment at LHC. In addition, the ANKE-ABS was used in Jülich to investigate a possible surface coating of the storage cell made of amorphous carbon. This revealed a high recombination rate of atoms in molecules with a simultaneous polarization retention of more than 70% [2].

Selected publications of 2024

[1] N. Faatz, R. Engels, C. Kannis, B. Breitkreutz, and H. Soltner, “Development of a complete spin filter for metastable hydrogen atoms and its isotopes,” *Physics Open*, vol. 22, p. 100248, 2025, doi: 10.1016/j.physo.2024.100248.

[2] T. El-Kordy *et al.*, “Amorphous carbon-coated storage cell tests for the polarized gas target at LHCb,” *Nucl. Instrum. Meth. A*, vol. 1068, p. 169707, 2024, doi: 10.1016/j.nima.2024.169707.

6.6 JEDI

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

Precision physics with the JEDI experiment: Highlights 2024.

The JEDI (Jülich Electric Dipole moment Investigations) collaboration was formed to carry out a long-term project for the measurement of the permanent electric dipole moments of charged particles in a storage ring. With the conclusion of the operation of COSY at the end of 2023, the activities of JEDI in 2024 mainly focused on finalizing data analysis and preparing publications. Several other publications drafts were submitted to journals in 2024:

- *Proof-of-principle demonstration of a pilot bunch comagnetometer in a stored-beam,* submitted to Physical Review Research
- *Maintaining a Resonance Condition of an RF Spin Rotator Through an Active Feedback Loop in a Storage Ring*, submitted to Phys. Rev. Accel. and Beams [1]
- *Compact beam position monitor using a segmented toroidal coil*, accepted for publication by Review of Scientific Instruments.

Furthermore, during 2024 two PhD and one master thesis were completed. Activities on the design of a new type of storage ring to measure electric dipole moments of charged hadrons are part in the “Physics Beyond Colliders” initiative at CERN and have been presented in talks at the Symposium of the NuPECC Long Range Plan 2024 for European Nuclear Physics (November 19, Brussels) and the KET workshop on “The Future of Non-Collider Particle Physics in Bad Honnef”.

Outlook 2025

We expect to submit publications on the following topics:

- Deuteron EDM measurement at COSY
- Publication for the design and need for a combined small electric/magnetic storage ring to measure electric dipole moments of charged hadron (part of PhD thesis of Saad Siddique)
- Possibility of axion searches at the ESR (Experimental Storage Ring) (PhD thesis of Daoning Gu)
- Investigation of the possibility to disentangle oscillating EDM and axion wind effect with storage ring experiments.

Selected publications of 2024

[1] N. N. Nikolaev *et al.*, “Spin decoherence and off-resonance behavior of radio-frequency-driven spin rotations in storage rings,” *Phys. Rev. Accel. Beams*, vol. 27, p. 111002, Nov. 2024, doi: 10.1103/PhysRevAccelBeams.27.111002.

6.7 Polarization study in antiproton production

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

It is proposed to investigate possible polarization effects in the production process of antiprotons. If the antiprotons are produced with sufficient polarization, then it might be feasible to generate a polarized antiproton beam by extracting the produced antiprotons at a finite scattering angle relative to the primary beam.

In 2024 a detection system was prepared for the P371 experiment at the CERN/PS east area test beam, which is scheduled for summer 2025. The polarization measurement will be performed by analyzing the angular distribution of the elastic antiproton-proton scattering in the Coulomb-Nuclear Interference (CNI) region. The detection system includes tracking systems, scintillating fibers and straw tubes, to determine the tracks of the beam particles and of the antiprotons scattered in a liquid hydrogen target. The antiprotons are produced by a 24 GeV/c proton beam hitting a solid target resulting in secondary particles extracted into a beam line, which will be adjusted to accept negatively charged particles with a momentum of 3.5 GeV/c, which mainly are pions and for a small fraction antiprotons. Online pion suppression will be achieved by an aerogel threshold Cherenkov detector and a DIRC detector. The detector components and the data acquisition system which is based on the new DOGMA modules are presently prepared and tested.

6.8 Contributions to experiments at Jefferson Lab

Authors : S. Schadmand (GSI) and J. Ritman (GSI, RUB and FZJ))

The GlueX experiment utilizes a linearly polarized photon beam with E = 8–9 GeV and a large acceptance spectrometer. FFN contributes to determining the line shape of the Λ(1405) in a combined analysis using the spin-isospin filter of the $\Sigma^0\pi^0$ decay channel and the Kp decay. This analysis includes the Λ(1520) in both branches. The positions in the complex plane and branching ratios of the theoretically expected two-pole structure is measured with high precision.

FFN scientists have also been involved in the CLAS electroproduction experiment at 12 GeV with a focus on meson transition form factors. Data taking and analysis, including analysis of photoproduction data from the 6 GeV era, are ongoing.

Outlook 2025

The physics reach of GlueX will be extended by the upcoming high luminosity run with an upgraded detector setup.

6.9 FFN-Bochum Electronics Lab

Authors : Thomas Sefzick (GSI)

The FFN Electronics Lab is located partly in Jülich and partly in Bochum. It contributes to two main topics: designing and building interface PCBs for the DOGMA based readout of the various detector components in the P371 test experiment at CERN mentioned above. Furthermore, the ELab is evaluating possible EPICS based slow control setups for the gas system of the CBM TRD. Several systems (*e.g.,* RevolutionPI, Beckhoff) are under examination.

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.

H. Elfner is deputy speaker of CRC-TR-211 representing Goethe University Frankfurt since July 2024 and has been named an Outstanding referee of APS 2024. She has organized the second edition of an EMMI workshop on "Probing dense baryonic matter with hadrons II: FAIR Phase-0" in February 2024 at GSI as well as a EMMI RRTF on „Understanding light (anti-)nuclei production at RHIC and LHC" at GSI in April 2024. M. Bleicher organized the FAIR School Latin America in January 2024 in Havana, Cuba and has been appointed to the scientific advisory board of SUBATECH in Nantes. E. Bratkovskaya and M. Bleicher were members of the Organizing Committee of the 10th International Symposium on Non-equilibrium Dynamics (NeD-2024) in November 2024 in Thailand.

E. Braktkovskaya and M. Bleicher are involved in the white paper on "Physics Opportunities with Proton and Pion Beams at GSI/FAIR" as a convenor/contributor of Chapter 7 "Hadrons and dileptons as probes of strongly interacting matter". The aim of the white paper is to outline the physics goals and opportunities using the hadronic beams in QCD-inspired physics studies which will be available at FAIR at energy scale ranging from few to tens of a GeV: p, d, π, (and potentially antiprotons). The objective is to cultivate an extensive physics program and to foster a community that is driven by the pursuit of comprehending the dynamics of strong QCD. The goal is to strengthen the impact in the closely interconnected realms of nuclear, hadron, and heavy-ion physics which is at the heart of GSI/FAIR.

Almudena Arcones was appointed Max-Planck-Fellow at the Max-Planck Institute for Nuclear Physics in Heidelberg and was promoted to W3 professor for Theoretical Astrophysics at the Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt. Andreas Bauswein declined an offer for a W3 professorship at the University Tuebingen to continue working at the GSI Nuclear Astrophysics and Structure department. Gabriel Martínez-Pinedo served in panel Fundamental Constituents of Matter (PE2) for the 2024 call of ERC Starting grants. An ERC Starting Grant was awarded to Zewei Xiong from the GSI Nuclear Astrophysics and Structure Department for the research project "Neutrino flavor Transformations in dense Astrophysical Environments" (NeuTrAE). The project aims to thoroughly assess the impact of neutrino flavor oscillations on heavy element nucleosynthesis in extreme astrophysical objects. The grant is valued at 1.5 million euros over the period of 2025-2030. Christine Collins, postdoctoral researcher at the Nuclear Astrophysics and Structure department funded by the ERC Synergy Grant "HeavyMetal," was awarded a Marie Skłodowska-Curie fellowship. Almudena Arcones was the main organiser of this year TALENT/DTP school on Nuclear Theory for Astrophysics including support from EMMI (ECT*, Trento, 15 July – 2 August 2024). The goal of this TALENT school was to provide the attendees with high level training on nuclear physics and nuclear astrophysics from various perspectives that include the Equation of State (EOS), neutron star mergers, and supernovae – and their combined impact in spearheading the brand-new era of multi-messenger astronomy. Key lecturers were Almudena Arcones, Bruno Giacomazzo, and Jorge Piekarewicz, as well as other experts in the various fields of relevance to the school. There were a total of 24 students (7 female, 17 male) all Doctoral researchers or young postdocs. From the doctoral researchers 6 were TU Darmstadt/GSI. There were 14 lecturers (6 female, 8 male). Andreas Bauswein organized a meeting of the ERC Synergy Grant HeavyMetal consortium (Paralia, Katerinis, Greece, 6-10 May 2024). The workshop was dedicated to various aspects of kilonovae and r-process nucleosynthesis. There was a total of 52 participants including external speakers reporting on new observational, experimental, and theoretical avenues to understand r-process element formation in neutron star mergers.

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 2024, major efforts went into the improved treatments of nuclear potentials and description of changes in the equation of state.

Highlights in 2024

The properties of nuclear matter at extreme densities are of high interest for the calculations of merging neutron stars. Similar conditions in terms of temperature and density can be explored in the laboratory with heavy-ion collisions at GSI. To extract information about the physics properties of interest, detailed microscopic modeling of the dynamics of such collisions is crucial. The collective flow of matter produced in heavy-ion collisions is sensitive to the equation of state of nuclear matter at finite density.

In a first study, the impact of the nuclear matter equation of state (EoS) on collective flow observables - directed flow (v_1) and elliptic flow (v_2)—of nucleons and light clusters in heavy-ion collisions at GeV beam energies has been investigated employing the Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) microscopic transport approach [1]. In this model, clusters are dynamically formed throughout the entire collision process via potential interactions between nucleons, with additional deuteron production occurring through hadronic kinetic reactions. We consider three different EoS implementations, realized via potential interactions: two static EoS, - 'soft' and 'hard,' which differ in their compressibility modulus, and a soft momentum-dependent EoS, calibrated using proton-nucleus (pA) elastic scattering data. Our findings indicate that momentum-dependent interactions have distinct effects on rapidity and transverse momentum spectra compared to their influence on flow coefficients (see Figure 51). The best agreement with experimental data from HADES and FOPI for the directed and elliptic flow of protons and light clusters is achieved using a momentum-dependent EoS. Additionally, we observe a scaling behavior of v_2 as a function of transverse momentum (p_T) with respect to atomic number (AA). Finally, we demonstrate that flow observables provide valuable insights into the underlying mechanisms of cluster formation.

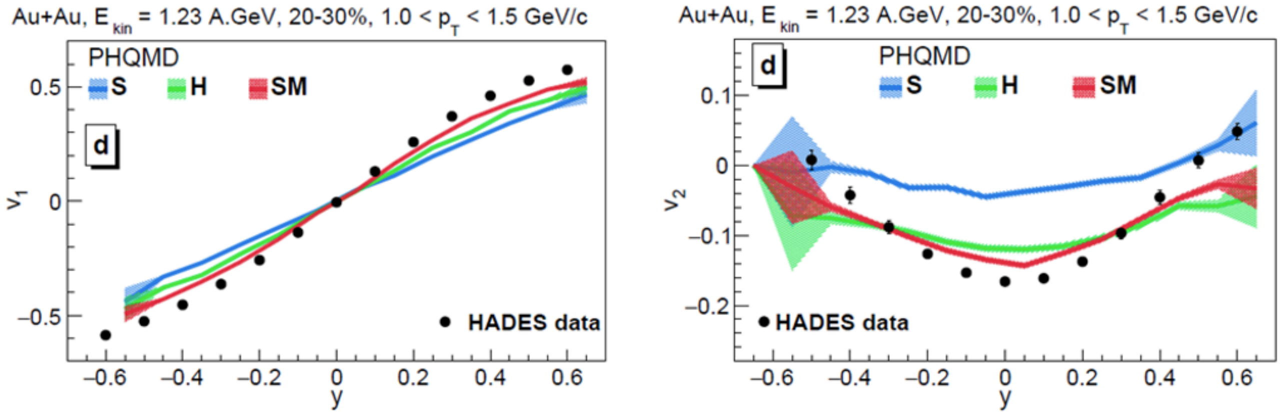


Figure 51: The directed flow v_1 (left) and elliptic flow v_2 of deuterons versus rapidity y in 20-30% central Au+Au collisions for p_T interval 1.0< p_T < 1.5 GeV/c for soft (blue), hard (green) and soft momentum dependent potentials.

The momentum dependence of the nuclear mean field has also been implemented in the BUU type hadronic transport approach SMASH (Simulating Many Accelerated Strongly-interacting Hadrons). We have performed an extensive comparison of calculations to the available FOPI data on Z=1 directed and elliptic flow measurements [2]. By carrying out a statistical analysis, it has been confirmed that at lower energies the soft equation of state fits very well, while higher energies and in particular the elliptic flow requires a harder equation of state. A similar analysis has been done with respect to the highly differential HADES measurements of collective flow for protons and deuterons [3]. From this comparison, we have performed a parameter extraction with a Bayesian analysis and obtain a rather stiff equation of state, while the symmetry energy is in agreement with prior findings (see Figure 52). This can be understood due to the large number of resonances in the SMASH transport code that effectively soften the equation of state. The momentum dependence of the implemented nuclear force is again crucial to get agreement with the data.

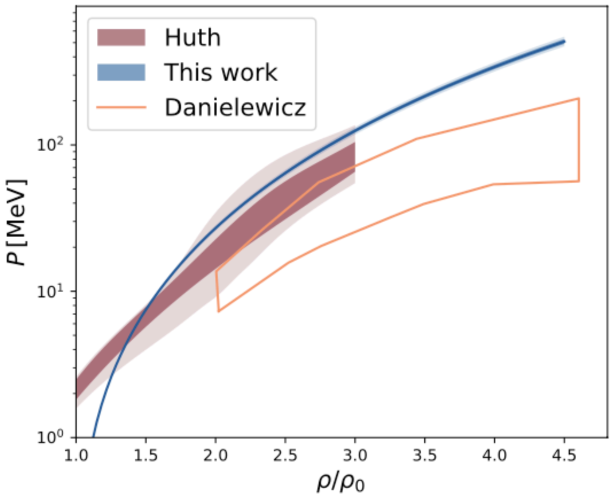


Figure 52: Equation of state of symmetric nuclear matter at vanishing temperature as a function of the baryon density.

The possibility of a first-order phase transition in the phase diagram of high density QCD has been at the center of decades-spanning experimental programs at several large collider facilities and is a major driver for the upcoming CBM experiment at FAIR. If a QCD phase transition occurs during the rapid expansion of the fireball created in a high energy collision of heavy nuclei, the resulting instabilities may lead to significant fluctuations of the baryon number. One remaining question here is whether the correlations and fluctuations, which will develop in coordinate space, can be measured in the final momentum space distributions and correlations. In our work [4] we introduced a high-density phase transition in the QMD (Quantum Molecular Dynamics) part of the non-equilibrium microscopic transport model UrQMD and simulated central heavy ion reactions expected at the CBM experiment at FAIR. We were able to observe the enhanced fluctuations of the baryon number through an enhancement of the scaled variance as shown in Figure 53.

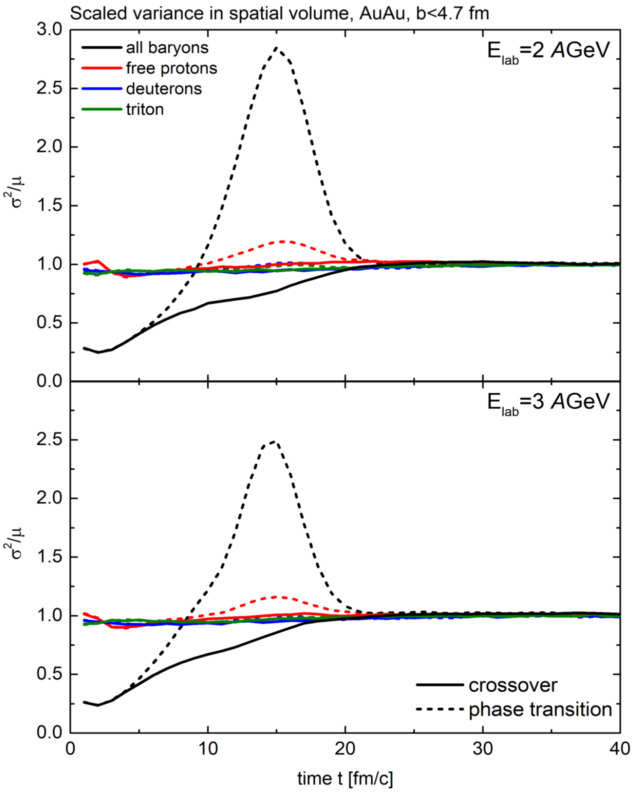


Figure 53: Time dependence of the scaled variance of baryons, protons and light nuclei in central collisions of heavy nuclei at beam energies expected at the SIS100 accelerator. The fluctuations with a phase transition (dashed lines) show a significant enhancement as compared to those without (solid lines)

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.

Outlook 2025

In 2025 we plan to extend our study on the influence of EoS on cluster production by extending our study from SIS energies of 1-1.5A GeV to 3-5A GeV energies which is directly related to future FAIR experiments.

It is also planned to improve the implementation of the QCD equation of state in the UrQMD transport model to include a momentum dependent and iso-spin dependent equation of state, based on a modern chiral mean field model [5]. Such a setup would allow the inference of the physical parameters of such an equation of state based on the newly available data from experiments at GSI and the STAR BES program.

The SMASH-vHLLE hybrid approach is going to be extended to lower (GSI/FAIR) beam energies by introducing dynamic fluidization of the initial state provided by hadronic transport. This will allow to investigate effects of a phase transition on observables.

Selected publications of 2024

[1] V. Kireyeu *et al.*, “Constraints on the equation-of-state from low energy heavy-ion collisions within the PHQMD microscopic approach with momentum-dependent potential,” Nov. 2024, doi: 10.48550/arXiv.2411.04969

[2] L. A. Tarasovičová, J. Mohs, A. Andronic, H. Elfner, and K.-H. Kampert, “Flow and equation of state of nuclear matter at E_{kin}/A = 0.25-1.5 GeV with the SMASH transport approach,” *Eur. Phys. J. A*, vol. 60, no. 11, p. 232, 2024, doi: 10.1140/epja/s10050-024-01445-w.

[3] J. Mohs, S. Spies, and H. Elfner, “Constraints on the Equation of State of Nuclear Matter from Systematically Comparing SMASH Calculations to HADES Data,” Sep. 2024, doi: 10.48550/arXiv.2409.16927

[4] T. Bumnedpan, J. Steinheimer, T. Reichert, C. Herold, A. Limphirat, and M. Bleicher, “Time evolution of light nuclei cumulants and ratios with a first-order phase transition in the UrQMD transport model,” *Phys. Rev. C*, vol. 111, no. 3, p. 034910, 2025, doi: 10.1103/PhysRevC.111.034910.

[5] J. Steinheimer, T. Reichert, Y. Nara, and M. Bleicher, “Momentum dependent potentials from a parity doubling CMF model in UrQMD: results on flow and particle production,” *J. Phys. G*, vol. 52, no. 3, p. 035103, 2025, doi: 10.1088/1361-6471/adab0b.

7.3 Theory: Hadron physics and QCD

Head: Matthias F. M. Lutz (GSI)

Author: Matthias F.M. Lutz

Highlights in 2024

A profound understanding of the theory describing the strong interactions is mandatory for making predictions for experiments and the interpretation of experimental data. The theory at GSI has performed state-of-the-art investigations in hadron spectroscopy and hadron structure. The theoretical effort is based on a modern methodology that combines Lattice QCD and chiral Effective Field Theory (EFT).

We performed an analysis of triangle- and box-loop contributions to the generalized potential in the scattering of Goldstone bosons off charmed mesons. Particular emphasis is put on the use of on-shell mass parameters in such contributions in terms of a renormalization scheme that ensures the absence of power-counting violating terms. This is achieved with a systematically extended set of Passarino-Veltman basis functions that leads to manifest power-counting conserving one-loop expressions and avoids the occurrence of superficial kinematical singularities. Compact expressions to chiral order three and four are presented that are particularly useful in coding such coupled-channel systems. Our formal results are generic and prepare analogous computations for other systems, like meson-baryon scattering from the chiral Lagrangian.[1]

We considered the axial-vector together with its induced pseudoscalar form factor of the nucleon as computed from the chiral Lagrangian with nucleon and isobar degrees of freedom. The form factors are evaluated at the one-loop level, where we use on-shell masses in the loop expressions. Our results were presented in terms of a novel set of basis functions that generalize the Passarino-Veltman scheme to the case where power-counting violating structures are to be subtracted. The particularly important role of the isobar degrees of freedom is emphasized. We obtain a significant and simultaneous fit to the available lattice QCD results based on flavor SU(2) ensembles for the baryon masses and form factors up to pion masses of about 500 MeV. Our fit includes sizeable finite volume effects that are implied by using in-box values for the hadron masses entering our one-loop expressions. We conclude that from flavor SU(2) ensembles it appears not possible to predict the empirical form factor at the desired precision. Effects from strange quarks are expected to remedy the situation.[2]

The baryon masses on Coordinate Lattice Simulations (CLS) ensembles were used to determine the Low-Energy Constants (LEC) that characterize quantum chromodynamics in the flavor-SU(3) limit with vanishing up, down, and strange quark masses. Here we reevaluate some of the baryon masses on flavor-symmetric ensembles with much-improved statistical precision, in particular for the decuplet states. These additional results then lead to a more significant chiral extrapolation of the lattice dataset to its chiral SU(3) limit. Our results are based on the chiral Lagrangian with baryon octet and decuplet fields considered at the one-loop level. Finite-box and discretization effects of the lattice data are considered systematically. We obtain values for the chiral limit of the pion decay constant and the isospin-limit of the quark-mass ratio compatible with the FLAG report.[3]

A lattice QCD computation of the coupled channel $\pi\Sigma - \bar{K}N$ scattering amplitudes in the $\Lambda(1405)$ region is detailed. Results are obtained using a single ensemble of gauge field configurations with $N_f = 2 + 1$ dynamical quark flavors and $m_\pi \approx 200$ MeV and $m_K \approx 487$ MeV. Hermitian correlation matrices using both single baryon and meson-baryon interpolating operators for a variety of different total momenta and irreducible representations are used. Several parametrizations of the two-channel scattering $K -$matrix are utilized to obtain the scattering amplitudes from the finite-volume spectrum. The amplitudes, continued to the complex energy plane, exhibit a virtual bound state below the $\pi\Sigma$ threshold and a resonance pole just below the $\bar{K}N$ threshold.[4][5]

Outlook

In the future, we plan to develop a sustainable method by combining the chiral coupled-channel approach with Lattice QCD, where we put our focus on meson-baryon systems as they are accessible with the pion beam at HADES or possibly with the proton beam program at CBM. Computations of such scattering observables on lattice ensembles with physical quark masses in large boxes require much more computing resources than those for unphysical large pion and kaon masses in small boxes. Therefore, a chiral extrapolated of such unphysical results to the physical case, with small pion masses and large box sizes, is to be established.

Selected publications of 2024

[1] T. Isken, X.-Y. Guo, Y. Heo, C. L. Korpa, and M. F. M. Lutz, “Triangle and box diagrams in coupled-channel systems from the chiral Lagrangian,” *Phys. Rev. D*, vol. 109, no. 3, p. 034032, 2024, doi: 10.1103/PhysRevD.109.034032.

[2] F. Hermsen, T. Isken, M. F. M. Lutz, and D. Thoma, “How much strangeness is needed for the axial-vector form factor of the nucleon?” *Phys. Rev. D*, vol. 109, no. 11, p. 114029, 2024, doi: 10.1103/PhysRevD.109.114029.

[3] M. F. M. Lutz, Y. Heo, and R. J. Hudspith, “QCD in the chiral SU(3) limit from baryon masses on lattice QCD ensembles.” 2024, doi: 10.48550/arXiv.2406.07442

[4] J. Bulava *et al.*, "Lattice QCD study of $\pi\Sigma$-KN scattering and the $\Lambda(1405)$ resonance," *Phys. Rev. D*, vol. 109, no. 1, p. 014511, 2024, doi: 10.1103/PhysRevD.109.014511.

[5] J. Bulava *et al.*, "Two-Pole Nature of the $\Lambda(1405)$ resonance from Lattice QCD," *Phys. Rev. Lett.*, vol. 132, no. 5, p. 051901, 2024, doi: 10.1103/PhysRevLett.132.051901.

7.4 Theory: Nuclear astrophysics and structure

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

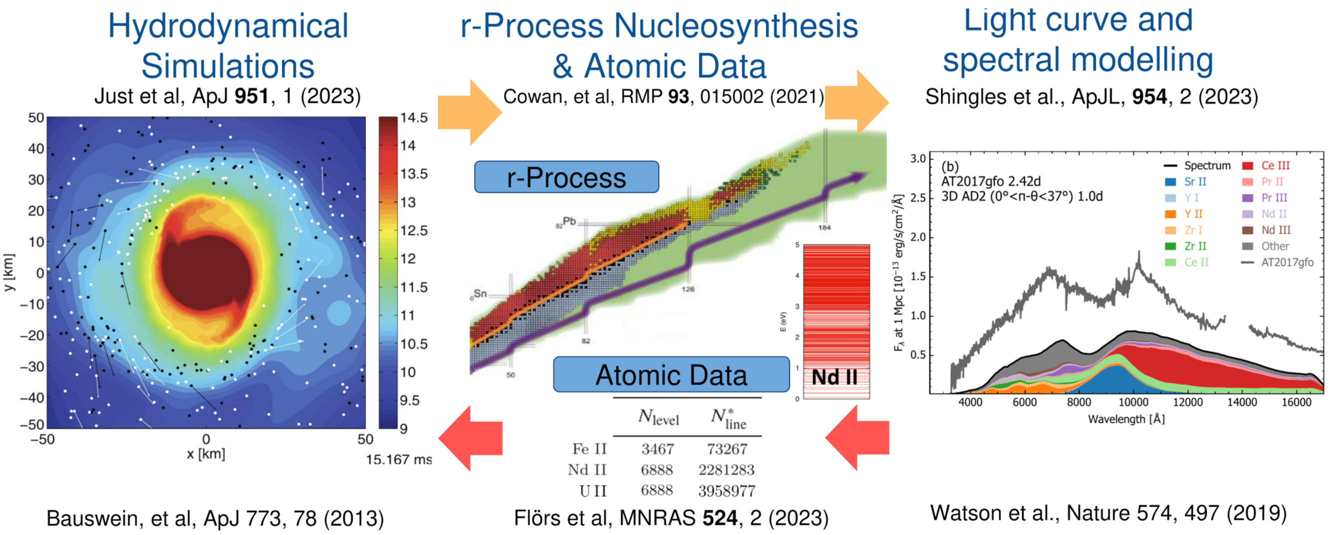
Authors: Andreas Bauswein and Gabriel Martínez-Pinedo

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 2024

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 modeling to generate synthetic kilonova light curves and spectra, which can be compared to observations. As a **highlight** and thanks to the funds provided by ERC Synergy, Advanced and Starting grants and a Leibniz prize, it has been possible to develop a complete and consistent **modeling pipeline** that includes all the ingredients discussed above (see Figure 54).



	N_{level}	N^*_{line}
Fe II	3467	73267
Nd II	6888	2281283
U II	6888	3958977

Figure 54: Illustration of the complete modeling pipeline developed by the nuclear astrophysics theory department that combines hydrodynamical simulations with r-process nucleosynthesis network calculations and Monte-Carlo radiative transfer modeling of kilonova light curves and spectra. The tools allow for the inclusion of advances in the theoretical description of the relevant nuclear and atomic processes and include new experimental information as it becomes available. It provides guidance to determine key experiments at GSI/FAIR.

As an illustration of the broad scientific possibilities of the new modelling pipeline, authors of Ref. [1] have looked at the geometry of the ejecta, which is highly relevant to use kilonovae to determine the Hubble constant.

A new relativistic code based on a moving-mesh technique for the simulation of neutron star mergers and other relativistic astrophysical systems has been developed, which is designed to minimize numerical artifacts and thus yield more robust and reliable models of the merger process and its ejecta [2]. Regarding microphysics aspects we have worked on the impact of the equation of state and weak interactions. For the later, work has also focused on the still incompletely understood impact of neutrino flavor conversions in supernova evolution [3]. Beyond-mean-field approaches that consistently treat first-forbidden and Gamow-Teller contributions to the beta-decay of r-process nuclei have been developed [4]. We have also put forward the first comprehensive study of hyperons in neutron star mergers[5]. Simulations of symmetric BNS mergers with a set of 9 different EOSs based on Skyrme density functionals have been performed to systematically investigate the impact of nuclear matter properties (effective nucleon mass, incompressibility, and symmetry energy at saturation density) on the merger dynamics, the fate of the remnant, disk formation, ejection of matter, and gravitational wave emission [6].

A new nucleosynthesis process denoted the νr-process has been suggested [7], Editors' Suggestion and highlighted in a Synopsis in Physics Magazine. It operates when neutron-rich material is exposed to a high flux of neutrinos. This process may be the solution to a long-standing issue related to the production of a group of rare isotopes present in the solar system but whose origin is still poorly understood, the so-called p-nuclei. Working in close collaboration with the Atomic, Quantum and Fundamental Physics department, we have provided the theoretical support necessary to convert the measurement of bound-beta decay of ^{205}Tl to astrophysical weak reaction rates connecting ^{205}Pb and ^{205}Tl and the determination of the cross section of solar-neutrinos on ^{205}Tl. This has allowed to study the production of ^{205}Pb by the s-process and its use to date the time necessary for the formation of the solar system from its progenitor giant molecular cloud [8]. Furthermore, the new neutrino cross section data can be used by the LOREX collaboration to study the solar neutrino flux, and hence the Sun's evolution, in the last million years [9]. In collaboration, with the Nuclear Spectroscopy department, we have studied the isospin dependence of effective charges by comparing data on electromagnetic transitions on ^{130}Cd and ^{98}Cd [10].

After previous works on magnetorotational supernovae investigating the nucleosynthesis of state-of-the-art magnetohydrodynamic models with fast rotation and different strength of the magnetic field, we have extended our study to different topologies of the magnetic field. In our models, we obtain a large variety of ejecta compositions reaching from iron nuclei up to nuclei of the third r-process peak. Our study includes an investigation of the impact of the nuclear physics input [11].

Outlook 2025

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 2024

[1] C. E. Collins *et al.*, "Towards inferring the geometry of kilonovae," *Monthly Notices of the Royal Astronomical Society*, vol. 529, no. 2, pp. 1333–1346, Apr. 2024, doi: 10.1093/mnras/stae571.

[2] G. Lioutas, A. Bauswein, T. Soultanis, R. Pakmor, V. Springel, and F. K. Röpke, "General relativistic moving-mesh hydrodynamic simulations with arepo and applications to neutron star mergers," *Monthly Notices of the Royal Astronomical Society*, vol. 528, no. 2, pp. 1906–1929, Feb. 2024, doi: 10.1093/mnras/stae057.

[3] Z. Xiong *et al.*, "Fast neutrino flavor conversions in a supernova: Emergence, evolution, and effects," *Phys. Rev. D*, vol. 109, no. 12, p. 123008, Jun. 2024, doi: 10.1103/PhysRevD.109.123008.

[4] C. E. P. Robin and G. Martínez-Pinedo, "Competition between allowed and first-forbidden β decay in r-process waiting-point nuclei within a relativistic beyond-mean-field approach," *Phys. Rev. C*, vol. 110, no. 6, p. 065803, Dec. 2024, doi: 10.1103/PhysRevC.110.065803.

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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 2024

A highlight in 2024 was the organization of the 3rd workshop [*] of a series of events within the newly established initiative “QCD at FAIR” for developing a new cross-community strong QCD-driven hadron physics program. Using proton beams exploited at FAIR with the SIS100 accelerator complex as well as pion beams at SIS18, future and existing experimental facilities such as CBM and HADES offer great opportunities for fundamental measurements in the field of hadron physics. These are partly also interdisciplinary connected to nuclear and heavy-ion physics. The proposed physics program aims to deepen our understanding of the fundamental mechanisms of hadron production in exclusively reconstructed reaction processes that also serve as a reference for heavy-ion and nuclear physics studies, and thus creating unique research opportunities across disciplines. It is a follow-up of earlier events that were held in February 2024 in Wuppertal, Germany and in June 2023 in Cracow, Poland. This recent workshop took place at GSI Darmstadt in November 2024, and the focus was on starting to write-up a White Paper that summarizes the outcome of the discussions among the nearly hundred experts of the field meanwhile involved.

Outlook 2025

This workshop will be followed-up by a 4th *concluding* workshop “*QCD at FAIR/GSI – Physics Opportunities with Proton and Pion Beams*” in June 2025 with the goal to finalize the White Paper, ensuring broad consensus on its contents. A vital aspect of this initiative is maintaining a coherent collaboration that integrates expertise from both, theoretical and experimental communities

[*] QCD at FAIR Workshop 2024, “*QCD at FAIR – Physics perspectives with hadron beams for the next decade (“first science”)*” Organizers: J. Messchendorp & F. Nerling, Nov. 11-14, 2024, GSI Darmstadt, Germany, for details see: https://indico.gsi.de/e/QCDatFAIR

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

The GSI Helmholtzzentrum für Schwerionenforschung GmbH and its accelerator Facility for Anti-proton and Ion Research (FAIR) provide an excellent environment for doctoral research and structured doctoral training. In strong cooperation with its partner universities, 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 2008. In addition to a variety of educational measures, the Graduate School provides individual support as primary contact and care center for doctoral researchers in its program. By the end of 2024, more than 350 doctoral students, conducting their research on GSI-FAIR related topics, are registered as participants in the HGS-HIRe program. 64 of them have been newly accepted for participation in the program of HGS-HIRe during 2024, 46 doctoral researchers affiliated with HGS-HIRe successfully finished their doctoral projects in 2024. 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, proved highly efficient in the daily work of the Graduate School.

Highlights in 2024

The resumption of the Graduate School's program activities after the challenging impact of the pandemic situation in the previous years has been continued in 2024. Compared to 2023, this led to an increase in the demand for individual travel support of the HGS-HIRe participants to participate in conferences and workshops. Furthermore, the residential face-to-face program has been expanded again. This is seconded by HGS-HIRe online events as established during the previous years of the pandemic. The following scientific training events, organized or offered by HGS-HIRe — partially in cooperation within the HGS-HIRe network — as residential face-to-face events in 2024, are particularly worth mentioning:

- HGS-HIRe Power Week on C++ Programming in Bad Münster am Stein / Ebernburg, January 29 - February 2, 2024 (workshop with introductory lectures, use cases and a strong focus on hands-on sessions; this scientific training course was organized in cooperation with the HGS-HIRe Participants Representatives)
- Joint SFB 1245 & HGS-HIRe Lecture Week on Studies of Nuclear Excited States in Darmstadt, April 15-19, 2024 (organized by the Students Representatives of the SFB 1245 and jointly offered within HGS-HIRe)
- International Summer Student Program at GSI-FAIR, July 22 - September 12, 2024 (training event for graduated students from GSI-FAIR partner countries, planned, organized and conducted in cooperation with a local team at GSI-FAIR)
- Joint SFB 1245 & HGS-HIRe Lecture Week on Algebraic Models in Quantum Mechanics in Darmstadt, November 20-22, 2024 (organized by the Students Representatives of the SFB 1245 and jointly offered within HGS-HIRe)
- Joint EURO-LABS & HGS-HIRe Lecture Week on Open Science and Data Management in Bad Münster am Stein / Ebernburg, November 24-29, 2024 (organized in cooperation with the EURO-LABS consortium and jointly offered as advanced training within EURO-LABS and HGS-HIRe)
- Joint RS-APS & HGS-HIRe Lecture Week on Machine Learning in Jena, November 25-28, 2024 (organized and offered in cooperation with Research School of Advanced Photon Science at the Helmholtz Institute in Jena)

In its well-established transferable skills training program, HGS-HIRe was able to keep the high number of supportive training events in 2024 on a similar level as in the previous year. Altogether, in 2024 nine interactive transferable skills courses as part of an integrated series of courses, covering beginner and advanced courses, with a total of more than 160 participants have been organized and conducted by HGS-HIRe together with the long-term trainer team from Great Britain. The courses were organized and offered as residential face-to-face courses and as 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. In particular, the following supporting information and training events complemented the program offers in 2024:

- 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 Young Entrepreneurs in Science workshop and various event offers by the Helmholtz Open Science Office (online and face-to-face)

In the HGS-HIRe Self-Service Center — 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 specialized scientific and technical aspects and methods, as the Helmholtz Summer School – From Data to Knowledge, the Helmholtz GPU Hackathon 2024, the HIDA & Helmholtz MDC Training Courses on Statistics and Fundamentals of Scientific Metadata and other series of computer and data science related lectures offered by the Helmholtz Information & Data Science Academy (HIDA) and the Center for Information Services and High Performance Computing (ZIH), respectively, supplemented the scientific training program of HGS-HIRe in 2024.

Outlook 2025

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, in 2024. For 2025, 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 behavior 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 summarized 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 2024: EMMI events

- EMMI Workshop "Strong interaction physics of heavy flavors," Organizers: R. Averbeck, M. Buballa, H.-W. Hammer, G. Moore, D. Mohler, January 14-20, 2024, Hirschegg, Austria
- EMMI Workshop "Probing dense baryonic matter with hadrons II: FAIR Phase-0," Organizers: A. Andronic, C. Blume, H. Elfner, M. Lorenz, February 19-21, 2024, Darmstadt, Germany
- ECT*-EMMI/GSI Workshop "Inaugural workshop on nuclear astrochemistry," Organizers: D. Bemmerer, D. Mifsud, E. Masha, N. Mason, February 26 - Mar 1, 2024, Trento, Italy
- EMMI RRTF "Deciphering many-body dynamics in mesoscopic quantum gases," Organizers: A. Mazeliauskas, T. Enss, G. Giacalone, S. Jochim, S. Masciocchi , March 18-21, 2024, Heidelberg, Germany
- EMMI RRTF "Understanding light (anti-)nuclei production at RHIC and LHC," Organizers: A. Caliva, H. Elfner, J. Schukraft, K. Blum, April 8-12, 2024, Darmstadt, Germany

- ECT*-EMMI/GSI Workshop "Bridging scales: At the crossroads among renormalisation group, multi-scale modelling, and deep learning," Organizers: A. Roggero, F. Pederiva, R. Potestio, R. Menichetti, April 15-19, 2024, Trento, Italy
- EMMI Workshop "Aspects of Criticality II," Organizers: F. Karsch, K. Redlich, J. Stachel, L. Turko, H. Satz, July 2-4, 2024, Wroclaw, Poland
- EMMI Physics Day, Organizers: K. Blaum, P. Braun-Munzinger, C. Ewerz, July 16, 2024, Darmstadt, Germany
- EMMI Workshop "Electroweak Physics InterseCtions - EPIC 2024," Organizers: S. Bacca, M. Cadeddu, F. Dordei, M. Gorshteyn, September 22-27, 2024, Sardinia, Italy
- EMMI Collaboration Meeting "Nuclear astrophysics at storage rings (NUCAR)," Organizers: Y.A. Litvinov, K. Blaum, P.J. Woods, R. Reifarth, J. Glorius, December 3-5, 2024, Darmstadt, Germany
- EMMI Workshop "Jefferson Lab at 22 GeV," Organizers: M. Battaglieri, M. Mirazita, A. Pilloni, P. Rossi, December 9-13, 2024, Frascati, Italy

9. Accelerators, Detectors, Electronics and IT

9.1 Activities of the Department Experiment Electronics

Head: Dr. Thomas Bretz (GSI)

Authors: 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 2024

Control Systems

Control Systems at GSI widely utilize National Instrument's (NI) LabVIEW. For cost reasons, the NI Enterprise Agreement is going to be terminated by the end of 2025. Therefore, the control systems group is continuously working on the migration of LabVIEW projects by consulting and active support.

Depending on the complexity of the control systems of the specific experiments, different strategies are being pursued:

For smaller setups like ARTEMIS and Targetscanner a migration to a combination of Python as programming language, MQTT as message protocol, telegraf as data relay, InfuxDB as storage database and Grafana for visualization has turned out to be the most promising way. In this context, PyAcdaq (a replacement for the LabVIEW frameworks CS and CS++) has been extended with a simple base class library based on asyncio (https://git.gsi.de/EKS/Python/ACDAQ/PyAcdaq).

Larger systems like SHIPTRAP will utilize EPICS in the future.

A special case is PHELIX which will continue with LabVIEW due to the size and complexity of the system. Here it is important to make the control system future-proof (for example via migrating from a modified version of the DIM protocol to MQTT). The work on these projects are still ongoing.

Consulting on EPICS in support of HADES, CBM, NUSTAR and PANDA is continued. Worth mentioning is the HADES Magnet Control System. The original implementation based on SPS and LabVIEW for monitoring and operation has been replaced with EPICS controls. In this context, the control hardware was refurbished as well and EPICS support for the newly installed control devices has been developed. The renewed magnet control system was successfully commissioned during the HADES beamtime in 2024.

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. During 2024, the layout group designed 90 printed circuit boards, of which 77 different printed circuit boards, which totaled to 5096 PCBs were assembled in our facilities.

Among these PCBs the first large batch of CBM-STS Front-End (named "FEB8") modules and around 2000 PCBs for the HADES-MDC-Frontend-Electronics have been manufactured. With that the first half of the MDC-detector has been equipped and successfully commissioned which is then used in the next HADES production beam time in 2025.

Analog Design

A specific analog front-end card ‘Twin_Peaks_CFD1’ was developed for the GSI DESPEC experiment with its Fast-Timing Array (FATIMA). For this purpose, it is necessary to obtain excellent information regarding the arrival time in combination with a clear spectroscopic distinction between gamma energies. The ‘Twin_Peaks_CFD1’ has 16 discrete analog constant fraction discriminators (CFDs) on a compact 12x10 cm^2 board.

A notable feature of the Twin_Peaks_CFD1 design is the use of off-the-shelf electronic components and low-cost FPGAs, emphasizing cost efficiency and accessibility.

Twin_Peaks_CFD1 is an innovative solution tailored to the unique requirements of the FATIMA array in the DESPEC experiment and similar setups. Its compact design, cost efficiency and integration into the existing infrastructure make it a valuable tool that enables precise timing measurements essential for advanced nuclear physics research.

In addition, the board seamlessly interfaces with the TAMEX4 Time-to-Digital Converter (TDC) board, an FPGA-based TDC widely used at GSI, and provides precise edge measurements with a resolution of 15 ps (rms).

These results were presented at the 2024 TWEPP conference in Glasgow [1].

Digital Electronics

The newly developed data acquisition system DOGMA was refined in 2024 and the first successful beam time experiments have been concluded.

A lab-setup of a DOGMA-DAQ with 24 “dogs” (768 channels) is shown in Figure 55.

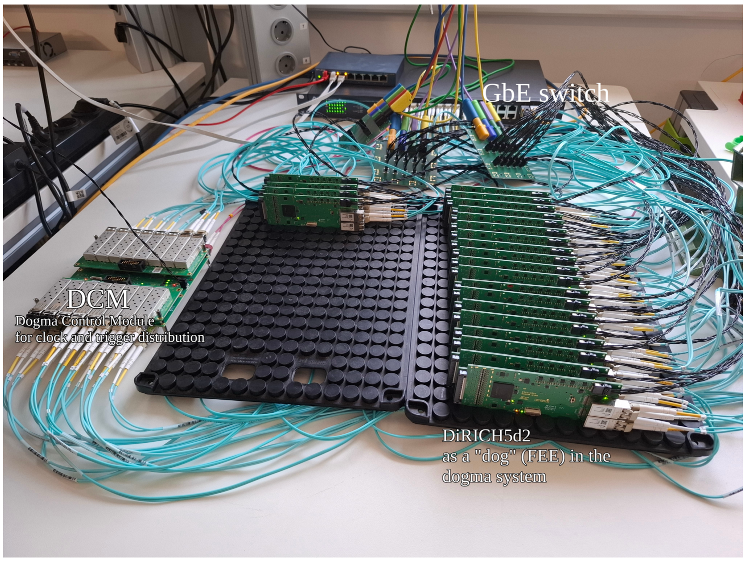

Figure 55: DOGMA DAQ-system, with 24 “dogs” and one central control module (”DCM”), with the 10GbE switch for data aggregation in the back.

The main features of the Dogma DAQ are fault tolerance (the DAQ always runs!), truly scalable (no trigger latency with growing system), based on commercially available data aggregation (Ethernet) and designed by the KISS principle (“keep it small and simple”).

More information is available at: https://dogma.gsi.de

Data Acquisition and Analysis

New developments from the data acquisition and -analysis group provided experiments at GSI/FAIR and abroad with substantial improvements with respect to performance and functionality.

Foremost are the FPGA firmware developments for the data concentrator board KINPEX of the Multi-Branch System (MBS). It comprises the uplift of PCI Express Gen 1 (4 x 2 Gb/s) to Gen 2 (4 x 5 Gb/s), the support of 64 bit addressing (replacing 32 bits) and a flexible frequency selection mechanism (2, 2.5, 3.15, 5, 6.25 Gb/s) for the data transport of its various GOSIP frontends.

In conjunction with the KINPEX enhancements, the data transfer rate has been enhanced from 2 Gb/s to 5 Gb/s for the 100 MHz pipelining ADC FEBEX4 and all versions of the Clock TDC (CTDC) within the GOSIP protocol.

In addition, the KINPEX kernel module was adapted to cope with the firmware updates reported above.

Together, all aforementioned developments enhance the data transfer capabilities by a factor of 2.5 and therefore provide a much better utilization of GSI/FAIR beams.

For VME based MBS system various improvements have been done mainly on our VME universal logic board VULOM. Especially, the new flexible slave address window capabilities and a new block move data transfer mode, allow setting up more complex and faster MBS systems based on the VME standard. In addition, the TRLO2 trigger firmware was adopted for MBS systems.

On the hardware sector two new boards have been designed and prototyped, in order to read out the new CTR16 chip, foreseen for the Super-FRS GemTPC beam position detectors.

New interface boards have been launched to change trigger and time stamp signals from copper to fiber to avoid possible common mode differences or grounding loops.

The new "plugin" — called ELDER — has been introduced for the analysis framework GO4. It facilitates experiment data analysis (online as well as offline) by allowing to combine predefined raw data unpackers and data processing components in a configuration file. It simplifies especially online data monitoring within GO4 with its fast and flexible histogram creation mechanism.

Furthermore, the readout of the new DAQ system DOGMA with DABC was implemented and as a constant workload the ROOT web GUI has been enhanced and improved.

Application Specific Integrated Circuits (ASIC)

During 2024 a major step toward a technology utilizing smaller design structures has been made. The analog as well as the digital design environment was set up for the application of the TSMC 65 nm CMOS technology. A first ASIC containing several test structures utilizing this technology was designed and submitted for production.

In comparison to the 180 nm technology which was used for most GSI ASIC designs until now, 65 nm features a gain in speed and integration density while power consumption is reduced. On medium time-scales, we expect that TSMC 65 nm will become the default technology node and replaces the 180 nm technology for most future designs.

As the 18 years old bonding machine showed significant degradation over the past years, it was replaced by a state-of-the-art semi-automatic wire bonding machine for ASIC prototyping. Therefore, the ASIC design group did intensive market research in preparation for the tendering process. Finally, the new machine replaced the old one in the clean room in October.

In addition, some test ASICs were characterized in the electronics laboratory. Worth to mention is a charge pulser ASIC which can be used as a detector model for front-end testing. It is able to generate single pulses as well as pulse sequences on four channels with a defined charge quantum over a very large dynamic range. Possible applications are the quick test of readout electronics at the experiment, as well as the characterization of charge sensitive amplifier front ends in the laboratory.

Selected publication of 2024

[1] M. Wiebusch, "Design and implementation of a compact analog constant fraction discriminator for high-resolution timing in gamma-ray spectroscopy," *Journal of Instrumentation*, vol. 19, no. 12, p. C12009, Dec. 2024, doi: 10.1088/1748-0221/19/12/C12009.

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 while building increasing competence in state-of-the-art silicon tracking detectors.

Highlights in 2024

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.

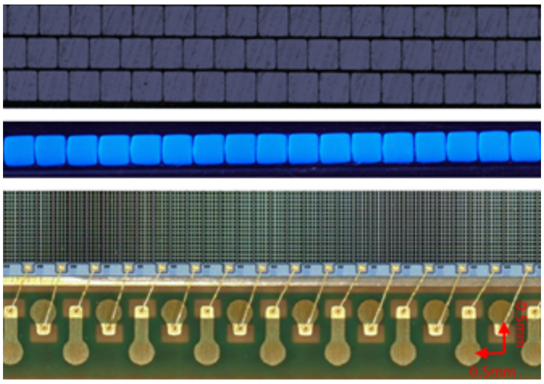

Figure 56: Cross-sectional view on a three-layer fiber ribbon (top), a one-layer fiber ribbon (middle) and the wire bonded SiPM array for readout.

Scintillating fiber trackers

Particle tracking at rates way above the one of TPCs can be carried out by scintillating fiber 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 fiber ribbons could be established. Scintillating fibers with square cross section were used to build up detection planes of highest homogeneity in material budget. The fiber ribbon comprising one or even three layers of fibers is read out by a one-dimensional array of Silicon Photomultipliers (SiPM) coupled to custom developed readout electronics (see Figure 56). The detector concept of scintillating fiber 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 utilized.

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 newly formed ECFA-DRD3 collaboration.

A first step in this direction was made by the ongoing realization of the Silicon Tracking Detector STS for CBM (see Figure 57), which forms a major contribution to FAIR. The detector integrates silicon 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]. 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.

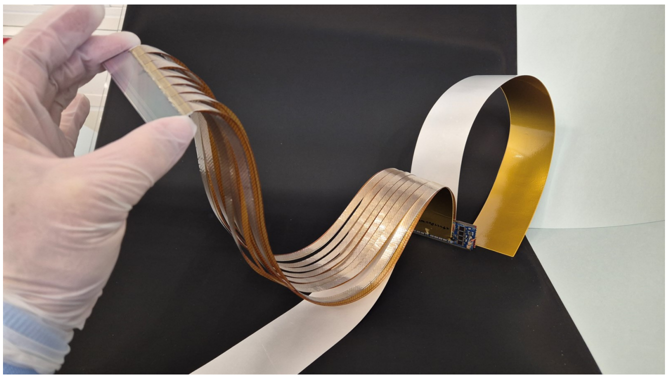

Figure 57: Example of a CBM-STS detector module where the small sensor will be allocated in the area of highest irradiation and the extremely long micro cables connect 2048 detector channels to the corresponding readout pre-amplifier chips outside the acceptance.

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) as well as the upgrade of the ALICE Inner Tracking System (ITS3). In collaboration with IPHC Strasbourg and Goethe University Frankfurt, the 60 µm thin MIMOSIS-1 MAPS prototype was developed, realized 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 $1x10^{14}$ n_{eq}/cm^2 was demonstrated in line with the CBM requirements[5]. Further, within the Helmholtz Innovation Pool project TANGERINE, the sensor's ability to perform limited particle identification through dE/dx was shown [6]. The integration of this sensor into an ultra-light vacuum compatible detector as required for fixed target heavy ion experiments was successfully studied. Moreover, the necessary immunity to single event effects was addressed [7] and could eventually be proven.

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 [8]. 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) [9].

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 optimized 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 realized 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 Super-FRS. Further, GSI supplied a diamond-based beam monitor for DESY.

Activities in 2024

A prototype for the HYDRA TPC was built and intensely tested at GSI. The final TPC is being commissioned and prepared for a first physics run scheduled in 2025.

A MUSIC detector being equipped with multiply segmented anodes was designed and successfully tested with a 1 AGeV ^{238}U primary beam at rates above 100 kHz. A one order of magnitude higher rate capability was reached with a similar detector relying on a GEM amplification stage [10] [11].

The current detector prototype of the high-pressure active target TPC was significantly expanded with respect to earlier designs to accommodate a wider variety of reactions and heavier beams up to Uranium. It was completed in 2024 and will be used by the AMBER collaboration in 2025 for performing proton radius measurements before being relocated to FAIR in 2026. GSI has contributed to the design and prototyping of critical components, including the thin composite beam windows, the inner electrodes, the 2t pressure vessel, and the pre-amplifiers.

Further, being also gaseous detectors, DTL delivered the very first batch of 12 particle detector combinations as high energy beam line monitors for the FAIR facility under construction. It is a GSI in-kind contribution where a total of 42 such devices will be employed at FAIR.

Dedicated prototypes of the scintillating fiber tracking planes designed to meet the specific requirements of the R3B applications in Early Science were constructed and successfully tested during beam times at GSI and earlier at COSY at FZ-Jülich. Serial production facilities were established and extensively optimized in 2024. Serial production of detection planes for the Super-FRS and R3B-PAS is scheduled to begin in 2025.

The silicon micro strip-based STS-project is now in full production mode. Modules are being assembled in series at GSI and KIT and further integrated onto ladders. By the end of 2024 about 39% of all 876 detector modules were assembled and tested.

Further, the first 7 out of 106 ladders comprising up to 10 modules each were assembled and extensively tested. Full integration of the CBM-STS is expected to last until the end of 2026.

In 2024, prototype LGAD sensors were integrated into concrete TOF applications [12], including an LGAD-based start reaction time detector for the HADES experiment, a beam monitoring system for the Superconducting Darmstadt Linear Accelerator (S-DALINAC) and an ion imaging system for medical applications for which an LGAD-based beam telescope was built [13].

Outlook 2025

The year 2025 will be mostly dominated by detector production, addressing the completion of the in-kind HEBT beam monitor production, the continued CBM STS assembly and the production of Super-FRS tracking detectors. These are MUSIC systems, GEM-TPC tracking devices but in view of the Early Science Program at Super-FRS also Scintillating Fiber tracking planes. On CBM-MVD integration, DTL will assist but the drivers are here University Frankfurt. DTL also engaged into providing 125 single crystal diamond detectors for the ERC Grant LISA led by Katrin Wimmer.

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9.3 Research of the IT Department

Head: Prof. Dr. Thorsten Kollegger (Goethe University Frankfurt & GSI)

Author: Mohammad Al-Turany

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 in the past year. This report aims to illuminate the key achievements and advancements made by different groups within the department. Central to the realization of the GSI/FAIR mission, the IT Department remains dedicated to fostering unparalleled expertise in the technical analysis, design, implementation, operation, and support of its vital computing infrastructure and services.

Highlights in 2024

Future-proof infrastructure supports the growing demand for the FAIR experiments

Our IT infrastructure, featuring the high-performance cluster and storage clusters, has proven its ability to effectively support the CBM experiment's online computational workload, as demonstrated by the parallel processing and 2 GB/s data rates achieved this year. This success, running alongside other group activities, highlights the adaptability of our resources. With the inherent scalability of the VIRGO cluster and the expansion capabilities of the Green IT Cube, we are well-positioned to accommodate the anticipated growth in the CBM (and other FAIR) experiment's infrastructure needs for future high-intensity data acquisition and analysis.

Integrated HPC Infrastructure Enables Rapid Large-Scale Plasma Physics Simulations

Collaborative efforts with GSI's Plasma Physics Group showcased the seamless operation of our HPC ecosystem. Utilizing the VIRGO computing cluster, high-speed network, and distributed storage, large-scale OpenMPI-based EPOCH simulations achieved exceptional performance. Efficient parallelisation across 40,000 CPUs facilitated the generation and parallel writing of 850 GB of output data in a mere three days, demonstrating the power of our integrated infrastructure for demanding scientific computations.

Enhanced Data Transfer Capabilities with Python-Based File Storage Queue (FSQ) Tools

The Storage/Data group has significantly improved the accessibility and usability of its File Storage Queue (FSQ) system for experiment data transport. Building upon the existing C-based API, a new Python-based API and accompanying command-line client application were developed in 2024. Performance tests conducted in late 2024 yielded promising results, demonstrating its viability as a high-performance alternative. Notably, the R3B experiment successfully adopted the new Python-based API for their data transfers, highlighting its practical utility and ease of integration for Python-centric experiment software.

Outlook 2025

Looking ahead to 2025, our focus remains steadfast on maintaining a robust and efficient IT infrastructure that underpins the scientific endeavors at GSI/FAIR. This includes continuous maintenance and upgrades of core components such as networking, storage, and central services to guarantee unwavering reliability and security. Furthermore, we are committed to ongoing efforts to optimize energy efficiency within the Green IT Cube and across our entire infrastructure, aligning with broader sustainability goals. To ensure proactive management and minimize disruptions, we will continue the further development and deployment of sophisticated monitoring and management tools for our HPC and storage infrastructure.

Optimisation and Scaling of the VIRGO Cluster

Ongoing efforts to optimise the performance and scalability of the VIRGO high-performance cluster to efficiently handle larger and more complex simulations and data analysis tasks.

Dedicated Resource Allocation for Online-Runs

As the CBM experiment progresses towards high-intensity runs, we anticipate further refinement of resource allocation strategies within the Slurm cluster to ensure dedicated and sustained performance for these critical periods, while minimising impact on other user groups.

Further Performance Optimisation of FSQ

Continuous performance testing and optimisation of both the C-based and Python-based FSQ APIs to ensure efficient and reliable data transport to Lustre and the tape archive, especially as data volumes from experiments continue to grow.

Wider Adoption of the Python-Based FSQ

Increased adoption of the new Python-based API and client for the File Storage Queue (FSQ) by various experiments, streamlining their data transfer workflows and improving ease of use for Python-centric analysis frameworks.

Selected publications of 2024

P1928R15 std::simd - Merge data-parallel types from the Parallelism TS 2, Matthias Kretz, 2024-11 (7 revisions in 2024)

P3299R3 Range constructors for std::simd Daniel Towner, Matthias Kretz, Ruslan Arutyunyan, 2024-12, (4 revisions in 2024)

P3287R2 Exploration of namespaces for std::simd, Matthias Kretz, 2024-11, (3 revisions in 2024)

P2781R5 std::constexpr_wrapper, Zach Laine, Matthias Kretz, Hana Dusíková 2024-11, (2 revisions in 2024)

P3488R1 Floating-Point Excess Precision, Matthias Kretz, 2024-11, (2 revisions in 2024)

9.4 Activities in technology transfer at GSI and FAIR

Head: Dr. Tobias Engert (GSI)

Authors: Dr. T. Engert, Dr. K. Göbel, Dr. M. Bauer, Dr. A. Surowiec, A. Haag, J. Bardak, M. Spreng, Dr. I. Prokhorov, Dr. S. Utermann.

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 11 full-time equivalent (FTE) employees, including 8 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, ten projects have been funded by the Innovation Fund as feasibility studies, validation projects or pre-startup projects in various fields, including software development for beam dynamics, novel compact liquid ion sources, new processes for isotope enrichment for the production of radioisotopes, materials development for extreme environments, electronics, software for multidimensional data analysis and 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 center 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 Center for Artificial Intelligence “hessian.AI” and companies like NDC Data Center 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 secured with the Goethe University Frankfurt and the University of Saarland, focusing on high-performance computing. The Digital Open Lab will also serve as a platform for the CISPA-Helmholtz Center for Information Security to develop IT security applications, processes, and infrastructure.

Due to high demand, plans are underway to double the Lab’s capacity, supported by the installation of a second cooling system in 2024.

3D Range Modulators - VARIAN Project > Siemens Healthineers - Project Completion

The 3D Range Modulators project was successfully completed in collaboration with the Technical University of Mittelhessen (THM) and VARIAN. The goal was to develop and validate a clinical workflow for optimizing and producing personalized 3D range modulators for proton-FLASH therapy. The project focused on creating a new clinical procedure using a single radiation shot instead of multiple energy steps. A personalized 3D range modulator (3D-RM) was designed and optimized for each tumor shape using high-quality 3D printing.

The project was completed on schedule, and the results were transferred to VARIAN and its successor, Siemens Healthineers.

Co-Creation Project

The Helmholtz Institute Jena and GSI Technology Transfer, in cooperation with Active Fiber Systems GmbH, successfully applied for funding for the project “Innovation Partnership for High-Flux EUV Light Sources in Metrology and Imaging”. The project aims to develop high-performance EUV light sources and is expected to start in summer 2024.

The goal is to realize a new approach to generating laser-like EUV radiation, promising a two-orders-of-magnitude increase in performance compared to the current state of the art. By collaborating with industry partners like Carl Zeiss SMT GmbH and SPECS Surface Nano Analysis GmbH, the project aims to drive technological innovations, identify potential applications and markets, and integrate industrial perspectives into applied research.

The approved proposal enables the mobilization of necessary resources and expertise to explore the physical foundations and feasibility of the concept and realize a prototypical laboratory setup. Using co-creation methods and a joint exploitation strategy, the project aims to achieve targeted and application-oriented development, 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 Brennstoffzellen Technik gGmbH (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 Education and Research (BMBF), 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 BMBF, 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 analyze 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 Education and Research (BMBF) is a collaborative effort between GSI TTR, the Leibniz Institute's Innovation Center, 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.

Launch of the Helmholtz Innovation Platform Hi-Acts

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 centralized 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.

As an "enabler," Hi-Acts supports companies and applied research in leveraging this potential. The platform provides funding for concrete transfer measures, such as the yearly Use Case Initiatives Call, which offer €100,000 in funding for each partner center. These initiatives focus on integrating accelerator-based technologies into value chains, with a clear connection to the accelerators or facilitating their industrial use.

Recent examples of funded projects include a GSI biophysics project to simplify and optimize radiation hardening tests for space applications, and two further GSI initiatives for 2024: the development of the “Microbeam 2.0” microprobe for automated focused radiation hardening tests, and the “AI for precision x-rays” project, which aims to bring advanced x-ray techniques to industrial and medical applications using artificial intelligence (AI) and laser control systems.

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 involved in the European Technology Transfer Network “HEPTech” and collaborates with CERN on the digital event series HEPTrepreneurs. GSI continued to participate in this series, with multiple episodes conducted each year.

Since 2023, HEPTrepreneur Workshops have been also held on the GSI campus. Participants learned the basics of entrepreneurship and how science can have an impact on society over the course of three days. Start-Up Afternoon provided information on how to turn ideas into a business model and find funding. The event was supported by Innovectis, the transfer company of the Goethe University Frankfurt.

Regular internal training offers in the field of entrepreneurship are also provided, including online webinars and a physical training school that took place. The training school, organized in cooperation with the European technology transfer network HEPTech, focused on the basics of entrepreneurship and 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 58: View on FAIR construction Site in April 2025

Following the FAIR Council decision in March 2023 to finance and build the scenario First Science, the FAIR project (see Figure 58) is making excellent progress towards the completion of the Early Science configuration by the end of 2027 and the completion of the First Science configuration by the end of 2028 (see Figure 59). The extension towards First Science + (CBM experiment in addition to First Science until 2028) is also progressing step-by-step as soon as additional financing is made available by the FAIR Shareholders. Nevertheless, the full CBM funding depends on few Shareholders which still need to confirm their pending contribution.

The year 2024 was a pivotal year for the FAIR project, marked by significant milestones towards the completion of the First Science configuration. In April 2024 the concrete work has been successfully completed for all the approved buildings (all FAIR buildings except p-Linac, Collector Ring and HESR). The Technical Buildings Installation is progressing extremely well, with a targeted completion by the end of 2026. Subsequently, a step-by-step hand-over to the GSI Facility Management will be initiated.

On the accelerator side, the major milestone was the start of the installation activities. In January 2024, the first SIS100 power supply units (see Figure 61) have been installed into the SIS100 tunnel followed few weeks later by the transfer of the first SIS100 supra-conducting Dipole into the same tunnel and some HEBT magnets into the transfer tunnel from GSI to FAIR (see Figure 63).

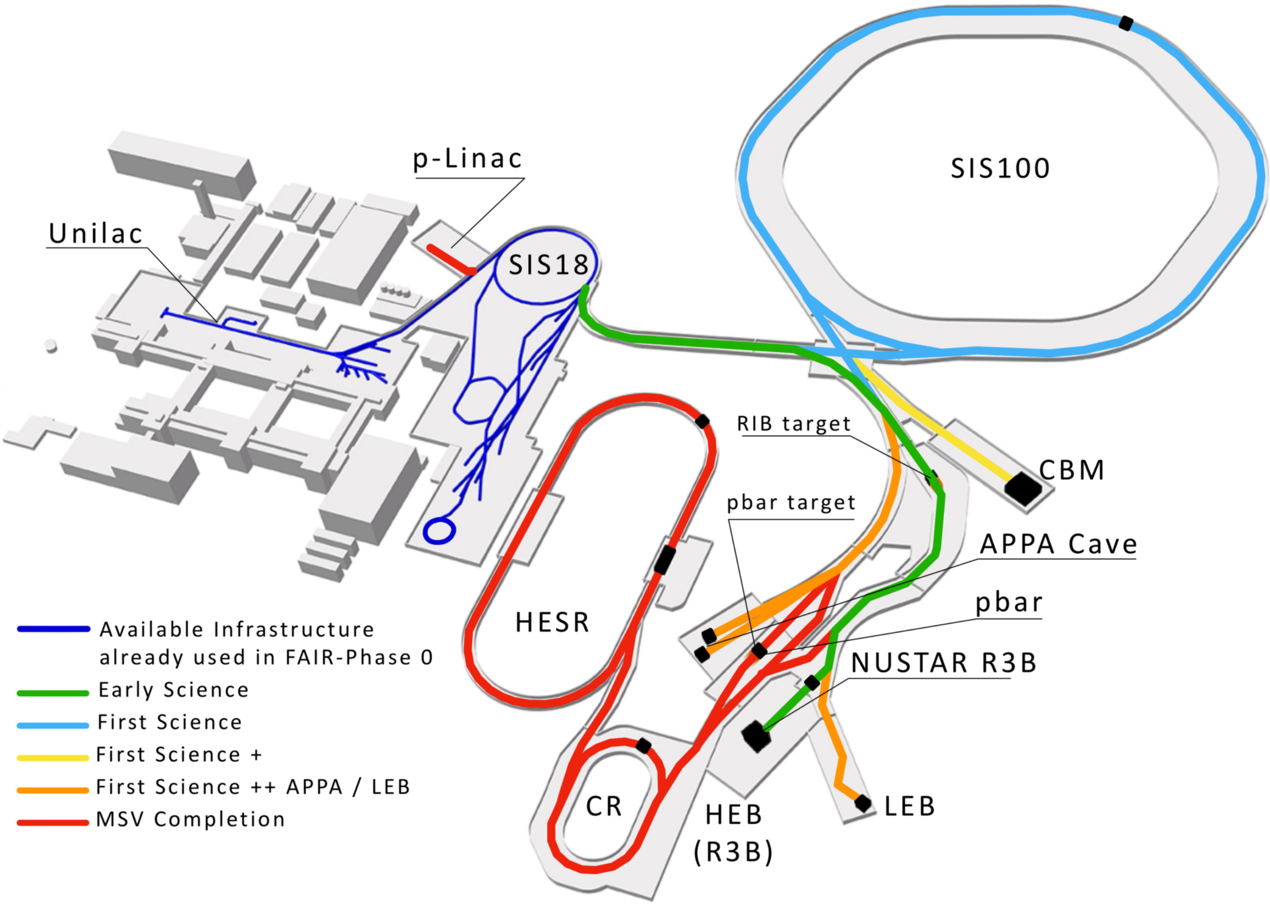


Figure 59: FAIR accelerator facilities with various entities and achievement steps

Figure 60: Air coolers installed on the main transfer building H0719A

Figure 61: First Power Supply Unit in the SIS100 tunnel

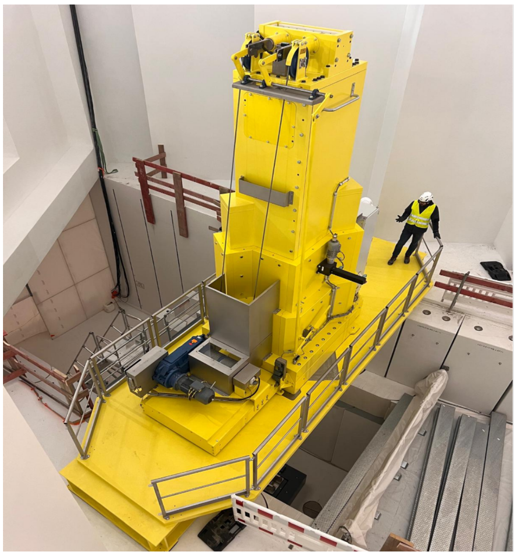


Figure 62: Super-FRS Flask delivered and installed on site

Figure 63: SIS100 dipoles positioned in the tunnel

10.2 SIS18 Accelerator: Developments

Head: Dr. Peter Spiller (GSI & FAIR)

Authors: P. Spiller, L. Bozyk, H. Welker, A. Krämer, C. Groß, J. Stadlmann, D. Ondreka

Acitivities of 2024

As a new approach, for smoothing the microstructure of the beam during slow extraction, a very high harmonic Rf cavity has been developed and installed in SIS18 (see Figure 64). Rf commissioning and beam tests were started in November 2023 and continued in several runs in collaboration with specific experiments in 2024.

Figure 64: The new micro spill smoothing cavity at installation in SIS18

Parallel to the new cavity, another concept for optimizing the time structure of the spill at slow extraction via a control loop around the KO exciter has been prepared. The system is able to generate an almost rectangular time structure at slow extraction by feedback. Moreover, it allows improving the spill microstructure by optimizing the excitation signal. For comparison, both techniques have been applied to beams generated for the HADES experiment. Investigations of the spill indicated that the parallel application of both approaches delivers the best spill microstructure when quantified by the spill duty factor. Analysis of the event rate by the experiment has confirmed excellent, so far, never reached beam quality and thereby a more efficient use of the provided beam intensity.

In order to assure a reliable operation for the FAIR Phase-0 and the SIS100 booster mode, a refurbishment of main technical systems has been launched. In 2022 and 2023, a major amount of IZ pumps and NEG pumps had been procured for replacing the old pumps in operation since the SIS18 commissioning. During the shutdown 2024, from sector S03 to S05, all IZ pumps have been exchanged and all Ti-pumps replaced by CapaciTorr-NEG pumps. Thereby, the static UHV pressure could be lowered in these sections from $5x10^{-11}$ to $1x10^{-11}$ mbar. An excellent static residual gas pressure is essential for the operation with low charge state heavy ions (e.g. the FAIR reference ion U^{28+}), as required for reaching the ultimate FAIR intensities. Besides the replacement of UHV system components, also the renewal of the aged magnet power converters has been launched. As a first step, the power converters for the SIS18 injection quadrupole magnets have been tendered. With the department beam instrumentation, a strategy for a refurbishment of the various beam instrumentation devices has been agreed.

With an improved machine model, the development of the fast-cycling booster operation for SIS100 has been continued in the last machine runs (see Figure 65). The influence of hysteresis, eddy currents, and other effects on the transmission has been investigated. So far, a repetition rate of about 2.5 Hz has been reached. The high repetition operation, in combination with short extraction times, is also an interesting option to enhance the average number of ions onto the FRS target.

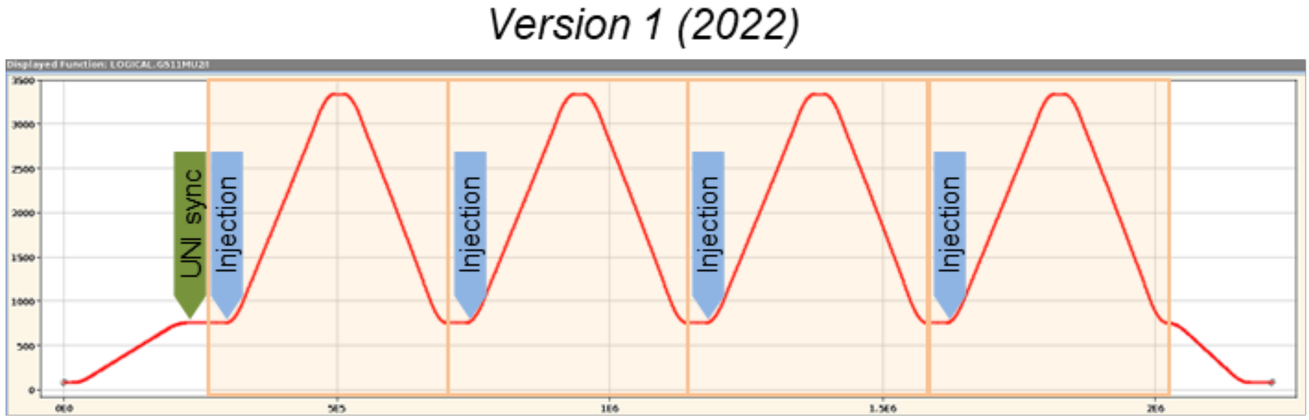


Figure 65: SIS18 high repetition booster cycle

To further stabilize the dynamic vacuum at operation with low charge state heavy ions, e.g., U^{28+} (FAIR reference ion) new concepts are under investigation. Cryogenic surfaces provide a huge pumping power, especially for heavy residual gas components, which have the largest cross-section for projectile ionization. The GSI made STRAHLSIM code has been improved for better modelling of the residual gas properties, especially in the transition areas from room-temperature to cryogenic sections. The STRAHLSIM simulations indicate a positive effect of cryogenic pumping for the survival of the beam in the FAIR booster operation. Therefore, a prototype cryogenic insert has been developed to be mounted around the SIS18 ion catchers. The first insert has been installed in the shutdown 2024 and will be tested with beam in 2025 (see Figure 66).

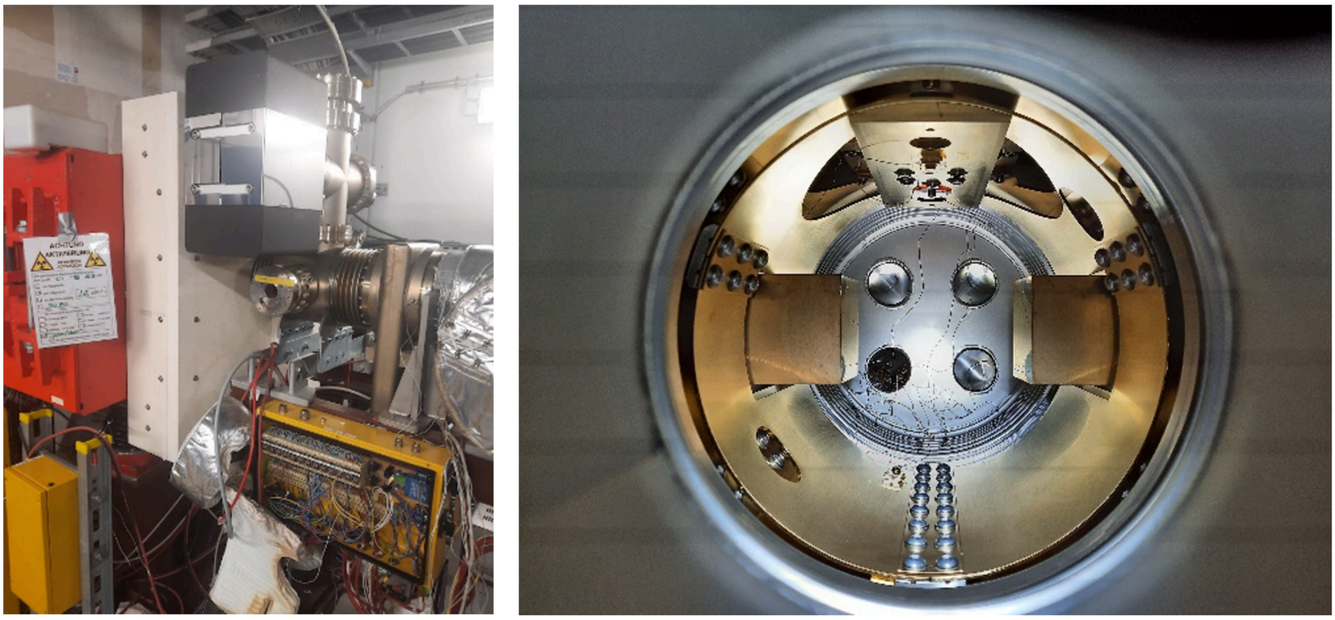


Figure 66: First cryogenic insert installed in SIS18 (stabilization of dynamic pressure)

Another development highlight respecting SIS18 is the worldwide first approach for a simultaneous acceleration of two different ion species in the same acceleration cycle. Accelerating two different ions may improve the precision of dose reproduction in the human tissue for cancer treatment. GSI could demonstrate the simultaneous acceleration and extraction with Carbon and He ions. In order to enable more flexibility in terms of the choice of ion species, a more demanding machine cycle using two separate beam injections requests from the UNILAC and comprising two individual Rf cycles is under development.

With the goal to meet all FAIR milestones, a list of future SIS18 upgrade measures has been developed.

10.3 SIS100 Accelerator project : Status

Head: Dr. Peter Spiller (GSI & FAIR)

Authors: P. Spiller, N. Pyka

Activities of 2024

The production and cold testing of sc quadrupole units has been continued at JINR, Russia. All agreed schedule milestones for the delivery of units were met and the integration of quadrupole modules at BNET, Würzburg was successfully served. Nevertheless, due to various reasons, relying and depending on the continuation of the deliveries from Russia is a high risk for the FAIR project. Therefore, it was decided to build up an alternative supply chain for the sc quadrupole units. In order to be prepared for a series production in industry, four prototype units have been contracted to company BNET. With contracting these units, all required tooling for the manufacturing of further series units will be prepared. The manufacturing of the four prototype units is almost completed, and the delivery will start in May.

With the units from JINR, the integration of quadrupole modules at BNET has been re-established and ramped up to higher rates. In parallel, several quadrupole modules were still tested at the GSI series test facility. A number of less important technical issues are still to be resolved during the execution of series integration. The module test facility in Salerno has been upgraded for operation and parallel testing with two feed-boxes. However, due to the delay created by the Corona and Ukraine crisis, the collaboration contract between GSI and INFN had to be amended by a new addendum covering the new expected testing period. Consisting of two dipoles and one quadrupole modules, representing one lattice cell of SIS100, a string-test has been built up at the GSI STF. The testing program has been continued with special focus on the mechanical stability of the assembly in different load situations, cross talk between bus bar systems, reinforcement of process lines and especially the string-test has been used to develop the overall installation procedures and work instructions for the tunnel. For the quench detection system, all quench detection boards have been delivered and tested.

Major progress has been achieved in the area of room-temperature magnets. The two large radiation hard quadrupole magnets, replacing a pair of sc quadrupole magnets in the extraction straight, have been accepted after FAT at Buckley, New Zealand and shipped to GSI (see Figure 67).

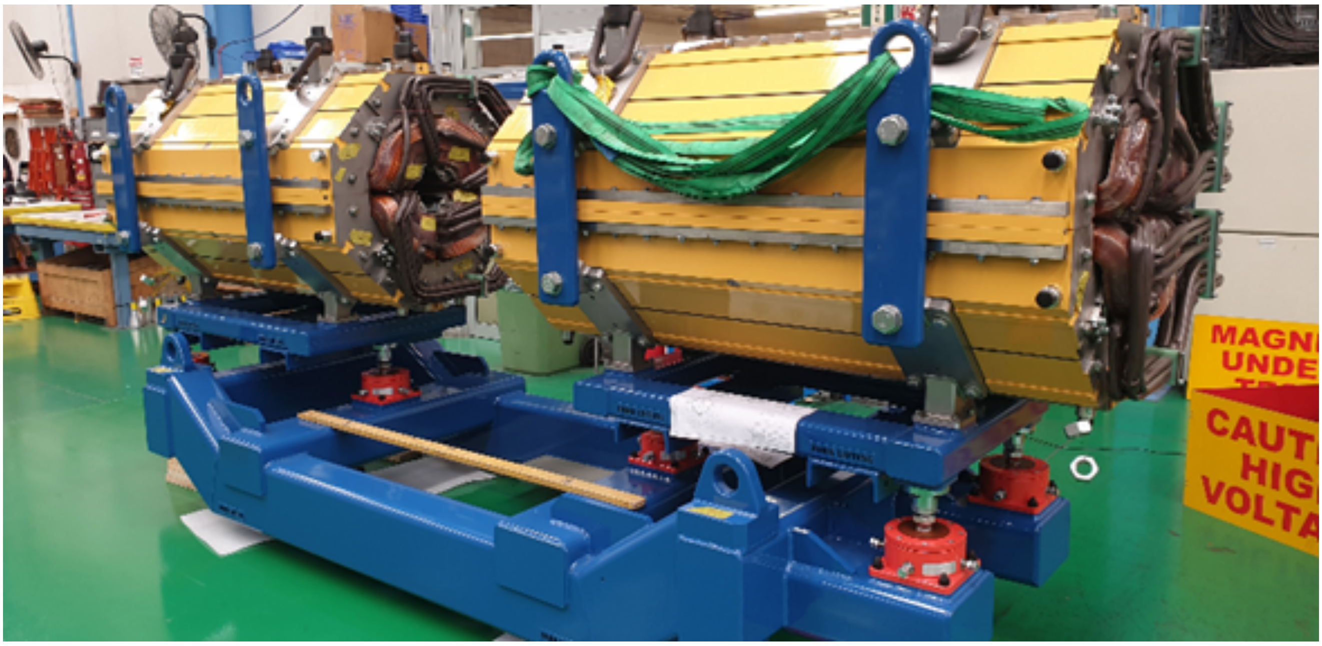


Figure 67: Radiation hard quadrupole magnets for the SIS100 extraction straight at FAT at Buckley, New Zeeland.

Also, the design and manufacturing of the extraction septa (Figure 68) at Elytt, Spain is progressing. A major achievement for the SIS100 project is the completion of the production of all components of the main dipole- and quadrupole power converter at GE, Berlin. The installation of the main power converter system has been launched on May 25th with the quench protection system above Niche 3. The overall installation process will take almost one year, followed by a first commissioning test using the internal energy dumping system. Further power converter series, such as the power converters for the gamma-t jump quadrupoles and the chromaticity sextupole magnets, have been contracted to industrial suppliers. The final acceptance process of the bunch compression cavities is running smoothly. Six of nine cavities have been accepted after successful power tests. A re-arrangement of the acceleration cavities positions from sector 6 to sector 3 enables an early continuation of the installation process. The manufacturing of the star-shaped quadrupole chambers needed for the quadrupole units in the extraction straight has been awarded to company RI. RI has already successfully managed the manufacturing of the elliptical quadrupole chambers made of the special, low permeability Boehler steel. The injection- and extraction kicker systems are challenging devices. During the acceptance tests of the injection kicker modules, major issues emerged with the HV pulse cables. After several HV brake throughs it became clear that the HV strength of the cables does not meet the requirements for both, the injections- and extraction kicker systems. Consequently, a world-wide search for an alternative cable has been conducted and in parallel technical meetings have been organized with Prysmian (former Draka) on the development of a new cable with optimized design. Besides the kicker systems, also the acceptance tests of the electrostatic extractions septum are significantly delayed by an erosion of the cathode surface observed after the UHV bake-out procedure (Figure 69).

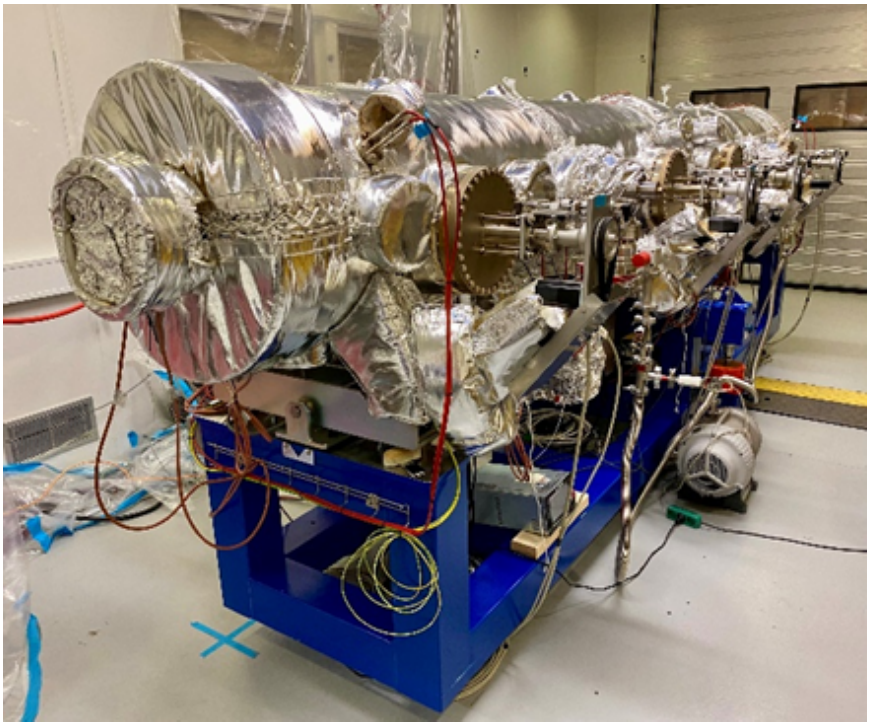


Figure 68: Electrostatic extraction septum during FAT at Danfysik, Denmark

The manufacturing of the current lead boxes at Inox, India is running smoothly. A FOS current lead box has been delivered to GSI and is presently at cold testing at the STF (Figure 4). WUST has also awarded a first feed box to Inox.

Figure 69: The FOS current lead box at cold testing at the GSI series test facility (STF)

Acknowledgement

The authors thank the outstanding engagement and work of the SIS100 work package leaders.

10.4 Division Super Fragment Separator

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

Author: V. Ricciardi (GSI)

Introduction

The Super FRagment Separator (Super-FRS) will provide to the scientific community clean and intense beams of unstable, short-lived nuclei, necessary to explore special properties of nuclides very far from the valley of stability. To achieve this goal, the Super-FRS as a machine faces several technological challenges: the realization of remotely controlled components with reliable performances in a highly radioactive environment (the “target area”), a superconducting-magnet system allowing for large apertures, and a diagnostic system with high-rate capability.

Activities of 2024

For most components, R&D was concluded already in 2022. 2024 was characterized mostly by progress in production and testing of components, and by the starting of installation in tunnel (see Figure 70).

Target area

By impinging the primary beam coming from the synchrotron into the production target rare “exotic” isotopes are produced. In order to achieve intense exotic beams, high primary-beam intensities are required, which cause a highly radioactive environment, posing technological challenges to target-area components. All components are hosted in a narrow iron tunnel acting as radiation shield. The iron shielding is necessary in order to reduce the radiation dose rate outside the target area to less than 0.5 mSv/h during Super-FRS operation. There are only a few centimeters clearance between the components and the sidewalls to limit air activation in tunnel. The iron shielding tunnel encloses: (i) the target chamber with graphite rotating production target, (ii) 3 radiation-hard normal conducting dipoles, 3 quadrupoles and 2 sextupoles, and (iii) 3 chambers hosting a beam catcher system with removable plugs. In-between the components, vacuum is closed by means of special pillow seals. All components – including the three 90-ton dipoles – are aligned to sub-millimeter precision via sophisticated alignment supports that are mechanically operated remotely from the roof of the iron tunnel.

The installation of the lateral iron shielding in target area started on May 7th 2024, directly after finalization of civil construction, and was completed on July 23rd.

Figure 70: View of the narrow iron shielding tunnel of Super-FRS target area.

The FAIR tender for the iron roof started in July 2024 and was awarded to Asturfeito S. A., Spain, in December 2024. The iron roof is the last thing to be installed in target area, once the machine is fully mounted and commissioned (without beam); afterwards remaining infrastructure installations can be completed on top of the iron roof. Finally, to close the tunnel along the beamline, two iron shielding blocks at the entrance and exit of target area are needed; they were produced by company Coswig GmbH, Germany; the Final Design Review (FDR) was approved in March 2024, the production was completed in December 2024.

The target chamber is an extremely complicated device, that embeds a rotating graphite target, a collimator, beam plugs, and instrumentation for beam monitoring. A water-cooling system ensures to keep the nominal temperature. The design was carried out by the KVI-Center for Advanced Radiation Technology (KVI-CART), at the University of Groningen, Netherland. The target chamber is being produced by Fantini Sud S.p.A., Italy. In 2024, a considerable progress in the manufacturing was registered.

The first bending after production target is achieved by radiation-resistant normal-conducting (nc) dipoles. One dipole, produced at BINP, Russia, is already on site. The French company Sigma Phi is producing other the two nc dipoles. In February 2024, the final design for the yokes was concluded and revised; manufacturing could start and is proceeding as planned. Also, the vacuum chambers inside the dipoles are technically challenging due to the high radiation, high energy deposition of remaining primary beam and high stresses in case of the use of pulsed beams. CNIM Systèmes Industriels (CSI) in France is producing vacuum chambers for the dipoles. The design phase was concluded with the approval of the FDR on August 2, 2024, and production has since begun. Chambers had to be built out of titanium to assure the requirements during operation.

Five multipoles are being produced by Buckley Systems, New Zealand. In February 2024, the FDR was approved, the production started and is running.

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. Because of the high beam power that comes with large intensity and/or short extraction times, the direct beam must not hit the material of a normal vacuum chamber but only the dedicated absorbers mounted inside the beam catcher chambers. BC are assigned as Indian in-kind contribution. The design of such a demanding system, including a careful selection of materials for the catchers withstanding the heat load and shock waves has been worked out with the CMERI Durgapur, India, the material science division, the target laboratory, and several other engineering departments at GSI during the last years. In November 2024, the production of the first BC chamber was completed by Trident Auto Components Priv. Ltd., India.

All alignment supports for components in target area are being produced by Fantini Sud s.p.a., Italy. Due to the complex interface with the superconducting magnets at the edges of target area, two additional special alignment supports are being produced, too.

A transport container (“flask”) will be used to remove activated plugs and targets from beamline and deposit them in the hot cell. In 2024, the German company Bilfinger Noell GmbH (BNG) finished the production of the flask, the Factory Acceptance Test (FAT) was approved in September. After FAT, due to its large dimension, the flask was dismounted and transported inside the target-area building. On November 21, the re-assembly in target area was completed.

To close beam vacuum in tight and highly shielded target area special developed components are required. Ten special removable plugs with integrated pillow seals will be placed in-between neighboring components. The production of plugs run throughout 2024 at Asturfeito S.A, Spain. In addition, 10 pillow seals and of 20 twenty special inflatable bellows were produced by MEWASA AG, Switzerland; the last FATs were done in November and December 2024 respectively.

Superconducting magnets system

All sections outside Target Area are in cryogenic environment. Key components for achieving early science (ES) objectives are 35 superconducting (sc) magnet modules [1] and the corresponding cryogenic system. There are 20 sc multiplets (a multiplet is a unit embedding several sc quadrupoles and various correctors; see Figure 71) produced by ASG Superconductors s.p.a., Italy, and 15 sc dipoles, produced by Elytt Energy S. L., Spain. Once produced, sc magnets are tested at cold (SAT test) [2] in a devoted cryogenic testing facility at CERN, specifically established in the frame of a Collaboration Agreement between GSI and CERN.

Having found systematic leaks in thermal shield of both sc multiplets and dipoles during the cold test (SAT) at CERN, dedicated task forces (GSI-CERN-ASG and GSI-CERN-Elytt) were established to envisage and drive the technical solution. Sophisticated X-Ray analysis methods were implemented at manufacturers. Eventually, insufficient quality of joints and too high mechanical stresses at the pipes were identified as root-cause, which let leaks occurring only at cold, therefore not being detectable during Factory Acceptance Test (FAT) at warm. Technical solutions were developed, including substitution of brazed copper by welded stainless steel pipes, measures to reduce the number of brazings, introduction of PIG welding, and additional mechanical supports. A new mock-up tests under cold and pressure conditions was implemented and all brazing joint samples must pass the multi-perspective X-ray inspection before the magnet could be shipped to CERN for cold testing. Being the leakages not detectable at warm, it was decided to repair the whole series magnets, i.e., also those that had been already produced and successfully tested at warm. In March 2024, the first repaired multiplet was shipped to CERN to be thoroughly and extensively tested at cold. After the successful completion of SAT test, demonstrating the accomplishment of the technical solution, the multiplet was shipped to GSI in August 2024. The production of eight further multiplets was completed in 2024; seven of them were shipped to CERN for testing. The first dipole with new joint technology arrived at CERN on February 16, 2024: no leakage was registered, magnetic measurements could be performed and cold test successfully concluded.

Figure 71: Superconducting dipole (left) and superconducting long multiplet (right) on testing benches at the testing facility at CERN.

Whereas multiplets integrate the vacuum pipe, sc-dipoles chambers will be inserted into the dipoles during pre-assembly activities before installation in tunnel. In November 2024, the two FoS vacuum chambers for sc dipoles produced at Thermal Vacuum Projects, S.L.U., Spain, passed the FAT. The tender of chambers for series dipoles was awarded to Fantini Sud S.p.A., Italy, on August 6th, 2024. The tender of two 9,75° chambers with a special Y-forked shape, for dipoles located at branching points, was awarded to CNIM Systèmes Industriels (CSI), France, on April 16th, 2024. The Conceptual Design Report was approved in December 2024.

Sc magnets are connected to FAIR cryogenic plant by means of the Local Cryogenic (LC) system (see Figure 72). The design of the whole Super-FRS LC system was developed by Wroclaw University of Science and Technology (WUST), Poland. For Early Science, the LC system comprises 5 branches (named T, P, M, H, G), a Branch Box, which is the starting point for distributing helium to the Super-FRS experimental branches, and an Auxiliary Cryogenics Piping System (ACPS), three piping lines for warm return process that run parallel to each branch for a total of about 1,2 km. WUST was originally in charge of parts of the production and installation of the cryogenics branches as well, together with BINP, Russia, as additional in-kind contributor. Since Russia was exempt from providing LC components and due to the increase of market prices, the procurement and installation of LC branches was re-scoped: branches T and P remained by Poland; branches M, H, and G were assigned to FAIR. In August 2024, Polish Ministry formally agreed to this solution. The FAIR tender for the procurement and installation of M, H, and G started in summer 2024. In December 2024, WUST awarded the production of Local-Cryogenics branch P to INOX India ltd, with KrioSystem Sp.z o.o. (Poland) as sub-supplier. In the meantime, in October 2024, WUST's sub-provider INOX India Ltd completed the production of branch T, whose components were shipped starting from November 2024. At GSI, a devoted cryogenic testing facility (Series Test Facility, STF) was set up in order to receive and test the first branch-T components.

Figure 72: Local Cryogenics Feed-Box for the cryogenic branch at the entrance of Super-FRS.

The tender of ACPS was awarded in February 2024 to DeMaCo Holland, that speedily produced the pipelines throughout 2024. In October 2024, the part of ACPS serving branch T was delivered to FAIR and installed in tunnel. DeMaCo Holland produced also the Branch Box: in February 2024, the FDR was approved and the manufacturing was completed by the end of the year.

Early science sc magnets need 116 power converters (grouped in 58 cabinets) to be powered. On 28 February 2024, India has withdrawn providing the power converters for quadrupoles (Q4) and dipoles (D2). The resulting FAIR tender was awarded to Jäger Elektronik GmbH, Germany, on May 5th, 2024. The purchasing of power convertors for correctors (C3) is still an in-kind contribution of India. Jäger Elektronik GmbH is also in charge of producing the Power Converters for the nc magnets, whose production advanced speedily in 2024.

Diagnostic system

Beam instrumentation and degraders will be hosted in vacuum "diagnostic" chambers placed in each focal plane. Two first diagnostic chambers, produced by Pfeiffer Vacuum Components & Solutions GmbH, Gottingen, Germany, were used for testing detectors and inserts throughout 2024. The FAIR tender for the production of 11 series diagnostic chambers was awarded to Streicher spol. s r.o., Czech Republic, in November 2024.

At focal planes FPF2 and FMF2, a degrader will be installed in the diagnostic chambers. Degraders are composed of material plates moved by linear and rotary drives. Drives represent the most complicate and expensive parts of the degraders. The FAIR tender for linear drives was awarded to the Italian company Dal-Ben s.p.a. in June 2024, the Conceptual Design Review (CDR) was approved in November 2024. The FAIR tender for rotary drives was awarded to T.E.E.S. srl, Italy, in August 2024, the CDR was approved in December 2024.

Concerning beam instrumentation and diagnostic, most former in-kind components are currently developed "in-house" at GSI/FAIR campus. Among these, plastic scintillators are produced as replacement of time-of-flight detectors for Early Science. A FoS plastic-scintillator detector was tested successfully with beam in February 2024, confirming the validly of design.

In May 2024, the Conceptual Design Review (CDR) was approved for the diamond detector at FPF4; the FDR of the diamond detector at FPF0 was approved in August 2024. In the meantime, the design of pre-amplifier was completed and the final printed-circuit-board is in production.

At the entrance of Super-FRS, the IPM detector will monitor the SIS-beam position. The detector uses a technology known at GSI and adapted for the large acceptance used of the beam-line focusing system in front of Super-FRS target. In 2024, the detector was produced and delivered in November 2024.

Time Projection Chambers (TPC) are planned as high-performant tracking detectors all along Super-FRS, as in-kind contribution of Finland. For the moment, only five high-performant tracking detectors (GEM-TPC) are included in the in-kind contract as Finnish contribution. In order to achieve the Early Science scope in time, a set of scintillating fibre tracking detectors are being produced in-house at GSI. The Conceptual Design Review (CDR) of fibre detectors was approved in March 2024; two FoS detectors were produced in order to be tested with beam in 2025. These detectors will be placed on two FoS ladders for position detectors produced by Finland, and shipped to GSI in July 2024. Drives for position detectors are a Swedish in-kind contribution. Key parts of these components are the M-Boxes and the power-drive controller (PDC), which were delivered to FAIR in 2024.

Two Beam Stopper Systems were produced by Axilon AG, Germany, and shipped to GSI in December 2023. In 2024, the Site Acceptance Test (SAT) was successfully concluded.

In 2024, further progress was also registered in the planning and acquisition of parts required to seal the beam vacuum. The ultimate, all-encompassing vacuum system for the entire Super-FRS was established [3]. Frame contract for valves, gauges, turbo pumps, ion getter pumps, roughing pumps were closed with German industrial providers (VAT Deutschland, Inficon, Leybold, Agilent).

Beyond Early Science

The Energy Buncher Spectrometer for secondary beam at low energies is part of the FAIR scope after Early Science. The Energy Buncher is composed of 5 sc multiplets, whose technology and design are similar to the multiplets currently produced by ASG, and of 3 large sc dipoles, whose parameters are quite different from the other sc dipoles. For these reasons, GSI contracted the design of the Energy Buncher dipole magnets to CEA Saclay, France, whose scientists already did the design of the sc dipoles and are in charge of the follow up of their production and testing. The availability of the design would allow a prompt starting of the tendering phase. This is important since the magnet production and testing of the EB system shall directly follow the current magnet production stage and therefore need to be prepared already by now. Although the geometric parameters of the EB dipoles are quite different from the dipoles in the separator the CEA colleagues could directly apply the design principles they developed for those magnets. In 2024, the design of the EB sc dipoles was concluded and the specifications approved [4].

Organisation

The Super-FRS Task Force Early Science was founded in May 2024 with an extended management board consisting of: Dr. Haik Simon, Dr. Martin Winkler, Dr. Ralf Gebel, Dr. Klaus Knie, and Stefan Menke. In addition, the new agile department SFC was founded as a branch of SFR, consisting of four teams dealing with different topics of the Super-FRS project such as: instrumentation, commissioning, magnets and controls, etc. The branch is embedded into the line structure of the division SFR, as well as in the project structure of the already existing Super-FRS Sub-Project.

Selected publications of 2024

[1] C.-E. Roux *et al.*, “Superconducting magnets for SIS100 and Super-FRS at FAIR – overview and progress,” F. Pilat, W. Fischer, R. Saethre, P. Anisimov, and I. Andrian, Eds., *15th International Particle Accelerator Conference*, Nashville (USA), 19 May 2024 - 24 May 2024; JACoW Publishing, May 2024, pp. 2862–2865 p. doi: 10.18429/JACOW-IPAC2024-WEPS71.

[2] E. Cho *et al.*, “Evaluation of magnetic performance of superconducting magnets for the superconducting fragment separator at FAIR,” *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–5, 2024, doi: 10.1109/TASC.2024.3350008.

[3] N. Kurichiyanil *et al.*, “Vacuum design of the super-FRS at FAIR,” *Journal of Physics: Conference Series*, vol. 2687, no. 8, p. 082031, Jan. 2024, doi: 10.1088/1742-6596/2687/8/082031.

[4] A. Madur *et al.*, “Status of preliminary design studies for the three superferric 30° bending magnets for the energy buncher of FAIR,” *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–5, 2024, doi: 10.1109/TASC.2024.3360212.

10.5 Division Commons

Head: Stefan Menke (GSI & FAIR)

Accelerator Controls System (ACO)

Author: Ralph Bär

The accelerator control system for FAIR, including the GSI injectors, is being designed and developed as in-kind contribution of the GSI Controls Group with in-kind contributions in collaboration with the Slovenian Tehnodrom consortium and the Polish company S2Innovation. During the second half of 2024, in line with the overall development and implementation strategy of the FAIR control system, the focus remains on the implementation, testing and commissioning of the future system and its hardware and software components at the existing GSI injector chain (UNILAC, SIS18, ESR, CRYRING, GSI-HEBT) for FAIR Phase 0.

Since the complete replacement of the old GSI accelerator control system (except UNILAC) in 2016-2018, the new system has already been successfully operated in four regular beam times between 2019 and 2025. The remaining legacy control system of the UNILAC section is scheduled to be replaced by FAIR standards until mid-2026.

In 2024, new operational functions were rolled out for the synchrotrons, storage rings and beam transport lines, as well as the overall performance of the system was improved. As a result, a basic version of the FAIR control system is already in use and can operate for the FAIR Phase-0 beam times today, ahead of the commissioning of the new FAIR machines.

Architecture, basic concepts and general system design have so far revealed no fundamental problems or showstoppers. Central systems of the control system architecture operate reliably and stably despite some technical and performance limits in the individual controls subcomponents that can be overcome during commissioning and operation. The subsequent technical revisions or re-designs of these subsystems required are ongoing, but do not have a major impact on the FAIR project progress either from a technical nor from project schedule execution perspective.

Overall, significant progress has been made in 2024 on all control system subprojects. Specific highlights are:

FAIR Control Centre (FCC)

The civil construction of the FAIR Control Centre (see Figure 73) is progressing rapidly. The fully digital control room is designed according to state-of-the-art principles of control room engineering, incorporating knowledges and experiences gained from other accelerator facilities, such as CERN. The technical design of the control room and its components has been completed and the procurement process for the first key components, starting with the operator consoles, is well advanced for early 2025. Installation of the control room equipment is scheduled by the end of 2025.

Figure 73: FCC building and main control room

Control System modernization of UNILAC injector

In 2024, significant progress was made in replacement of the UNILAC control system, the last part of the GSI injector chain to be modernized. By the end of 2024, the existing legacy system, with the exception of field layer equipment, is prepared to be completely replaced. The aim is to set up a seamless and unified control system for the FAIR installation's injector. Test campaigns without beam (dry-runs) and with beam have shown that implemented software concepts, functions and physics modelling of the UNILAC are adequate. The Control Systems Department, along with other accelerator departments, is working diligently to complete the remaining development works to replace legacy hardware by software solutions. The completion of this project will enable the UNILAC accelerator to be operated from the fully digital FAIR control room starting in 2026.

Beamline Vacuum Control

The design and implementation of the beamline vacuum control system is mainly a Slovenian in-kind contribution in collaboration with the GSI Industrial Controls team (ACO/IND). The system is based on industrial automation components (PLC) and bases on the UNICOS SCADA system, which is also used in other FAIR subsystems like cryogenic controls. In March 2025, the last industrial controls cabinets including the PLC and SCADA software, are delivered to GSI/FAIR (see Figure 74).

Figure 74: Vacuum control cabinets by Slovenian In-Kind partner

Beam Diagnostics (BEA)

Authors: Marcus Schwickert and Andreas Reiter

Accelerator operations and operation of the infrastructure support

In 2024, the support activities of BEA department for accelerator operations concentrated on improvements for beamline trims and better availability of diagnostic devices.

As part of a long-term upgrade project, a new, GSI-built acquisition system with digital camera readout (CUPID) has been integrated. The ongoing CUPID upgrade of the high-energy beam transport lines (HEST) of GSI has progressed significantly. Moreover, several scintillating screens needed refurbishment so that the scintillator material has been replaced at neuralgic points, e.g., at SIS18 extraction.

At UNILAC, better tools for measurement of the longitudinal phase space were in the focus. Thus, several machine studies using the GSI-built fast Faraday-cups (FFC) with 10 GHz bandwidth were carried out and yielded a great amount of data, see Figure 75. A dedicated graphical user interface for FFC readout is currently under development.

Figure 75: 3d-printed Fast Faraday-Cup

Intricate data analysis is still ongoing to disentangle the influence of various RF devices, like bunchers and accelerating cavities. For optimizations of beam matching and multi-turn injection into SIS18, it is foreseen to install two bunch-shape monitors (BSM, Feschenko-type) at Unilac and transfer channel, respectively. After successful repair at Forschungszentrum Jülich, one BSM was mounted and re-commissioned with beam at Unilac. In preparation of the foreseen further BSM installation, cabling works were carried out at the installation locations.

In view of the upcoming move of the main control room into the new FAIR Control Center (FCC), all beam diagnostic devices need to be controlled by FESA classes and thus fully integrated into the new accelerator control system. Many devices had already been modernized in the past.

However, the modernization of the very fundamental macropulse selector system (MAPS) for the readout of 60+ beam current transformers in UNILAC is still ongoing in 2025. The outdated front-end data acquisition hardware will be replaced with modern µTCA acquisition modules and seamlessly integrated using FESA and the FAIR timing system. After the production of purpose-built electronic modules in autumn 2024, the first hardware tests of the MAPS electronic boards have already yielded very good results during the 2024 machine experiments and will be continued during the beam time 2025. Furthermore, a new software for the online readout of all UNILAC beam position monitors named UNIPOS was developed and thoroughly tested in beam time 2024.

Research in accelerators, detectors, electronics and IT

During the 2024 beam time, BEA department conducted several machine experiments to test novel detectors and readout systems for FAIR.

An important step in measuring the bunch lengths of non-relativistic beams at Unilac were beam tests applying the fast Faraday-cups (FFC) with additive manufactured collector, which led to a new design of a tapered FFC. The availability of purpose-built FFCs in Unilac is crucial for future improvements and parameter optimizations concerning the longitudinal phase space.

In the past years, BEA department had made several successful experiments with ZnO(In) ceramic insulator as a radiation hard scintillating material for ultrafast particle counters. In 2024 beam time, a dedicated experiment was conducted to examine if commercially available ZnO(Ga) powder scintillators could be used as an alternative. The ZnO(Ga) powder material irradiated with a 300 MeV/u uranium beam showed a significantly lower light yield and stability problems. Thus, considerable development efforts are necessary to achieve similarly good detector properties as with the ZnO(In) ceramics.

The newly developed spill optimization system (SOS) for SIS18 has taken a major step forward [1]. Beam tests were carried out with 500 MeV/u uranium ions and $5 \cdot 10^7$ particles/spill. The effects for spill smoothing with tune wobbling and sine excitation were compared for two extraction modes, i.e., RF knock-out extraction and quadrupole-driven extraction. As a result, the SOS system passed the tests for both extraction modes. With an initial version of the graphical user interface, the system has been optimized for use as a standard operating tool in the future beam times.

In the frame of beam tests with a novel spill smoothing 81 MHz cavity in SIS18, BEA department supported the performance tests with detailed measurements of the spill quality during quadrupole-driven slow extraction. The slow extracted 300 MeV/u nitrogen beam was investigated using a purpose-built TDC acquisition module to detect the particle arrival time w.r.t. the RF phases with time resolution of about 100 ps. This high-performance setup clearly indicated that the smoothing cavity significantly improved the spill quality. Detailed simulations are ongoing in 2025 to confirm the findings.

Moreover, the first-of-series unit of the cryogenic current comparator, which is a German in-kind contribution to FAIR, was successfully tested with beam. The tests were conducted using a novel Dual Core CCC sensor, which showed significant improvements regarding noise floor and current resolution [2]. Measurements with slow extracted beams confirmed an increased bandwidth and a higher slew rate with respect to the single core sensor. The CCC beam tests were also used to check the full functionality of the new FESA-based data acquisition system.

Research and developments for the FAIR project

In 2024, the strong collaboration with Slovenian in-kind partners on software, hardware and infrastructure systems, like e.g., PLC-based controls for pressurized air drives, has continued. During a sequence of machine experiments at SIS18, dedicated FESA classes for diagnostic readout of fast current transformers, beam position monitors and ionization profile monitors were significantly improved and, in most cases, finalized for FAIR commissioning.

During beam time 2024, the new SIS100 ionization profile monitor (IPM) was thoroughly tested with beam and the novel readout software also built by the Slovenian in-kind partner yielded excellent measurement results. Moreover, µTCA-based readout hardware and new head-amplifiers for the ferrite core sensor were prepared for future beam tests. These devices will play an important role for precise intensity measurement of fast extracted beams in the HEBT beamlines.

GSI-teams also built the multi-wire proportional counters / ionization chambers (MWPC/IC), which are indispensable tools for the detection of slow extracted beams. A first batch of 14 MWPC/ICs, as required for Early Science, was finalized by GSI's detector laboratory, and passed successfully final quality checks, see Figure 76.

Figure 76: MWPC/IC detectors during pre-assembly (left) and fully assembled batch of 7 units (right).

In the future, current signals of particle detectors at FAIR will be read out using current-to-frequency converters (IFC). They are thus required for particle detectors for HEBT and SIS100. Development works of the new IFC version has made significant progress in 2024 and led to a new PCB design. It is now based on state-of-the art electronic parts and helps to overcome calibration problems due to thermal effects observed in previous IFC versions. A following benchmark production of 40 units by the Slovenian partner was successful and the need for HEBT detectors is now covered. Production start of the large IFC series of about 350 units for all FAIR subprojects is scheduled for the 2nd half of 2025 after completion of further hardware developments.

The layout of HEBT beam diagnostics includes 4 cryogenic current comparators (CCC) for the precise, non-intercepting detection of beam currents in the nano-Ampere range. The development of this unique detector for FAIR was finalized in 2024 by the CCC collaboration. Long-term cryogenic tests of the CCC first-of-series showed that the new cryostat design combined with a powerful re-liquefier enables a CCC stand an alone operation.

Once this major quality gate reached, purchase of the second cryostat and liquefier is being prepared since early 2025. Forming important infrastructure for several diagnostic devices, the final design of the high-voltage supply system was concluded. An international call for tender was launched for the purchase of the series of the high-voltage supply system. Operation of the gas-filled MWPC/IC detectors requires a reliable supply of high-purity detector gas. Thus, an industrial partner was contracted to design and produce a detector gas distribution system for the supply of Ar/CO_2 gas. At the end of 2024, the contract reached an important milestone with the successful FAT of the first-of-series devices of the detector gas supply system.

Following the completion of the simulation works for the final design of the SIS100 Schottky pick-ups in 2024, the layout of the detector and vacuum chamber was fixed. Manufacture of the complete Schottky setup is scheduled until end of 2025. Similarly, the design of the SIS100 beam stoppers was finished, completing the first-turn diagnostic devices required for beam commissioning of SIS100. Tunnel electronics, like front-end controllers for profile grids or pre-amplifiers for beam position monitors, will be placed in 84 dedicated niches around the SIS100 accelerator tunnel. The related electronic devices will be mounted in specially designed mini-racks. First prototypes of these mini-racks were equipped with electronics, and series assembly of all 84 mini-racks will be accomplished in the first half of 2025.

Cryogenics (CRY)

Author: Holger Kollmus

The technical department Commons Cryogenics (CRY) is responsible for the cryogenic helium supply of superconducting magnets and cavities. CRY operates a prototype test facility (PTF), a series test facility (STF), the Helium Supply Unit (HeSu) and two more cryo plants for R3B GLAD magnet testing and for the cooling of the CRYRING electron cooler solenoid. The main future customers at FAIR are the SIS100 and the Super-FRS with a total helium inventory of about eight tons.

Furthermore, the department is responsible for the so-called local cryogenics assigned to the FAIR sub-projects SIS100 and Super-FRS. The year 2024 is marked by the following main activities:

Cryogenic Infrastructure for the Series Test Facility (STF)

The STF has an overall cooling capacity of 1.5 kW @ 4 K equivalent and is equipped with four test benches for magnet testing and one universal connection box. Up to late 2024, the plant has about 60.000 hours of operation. All 110 SIS100 dipole magnets and all 18 SIS100 current lead pairs were tested so far. In 2024, local cryogenic components for SIS100 and for the Super-FRS, like by-pass lines and recently a Super-FRS feed box assembly were tested at the STF (see Figure 77). The Super-FRS feed box assembly, see Figure 77, consists of a transfer line connected to a feed box, an end box and the jumper connection to the magnet. All parts belong to the Super-FRS T-branch are a Polish in-kind contribution manufactured at INOX India.

Moreover, further SIS100 quadrupoles, a so-called string, an assembly of two SIS100 dipoles and one SIS100 quadrupole module are continued being tested. Furthermore, a test of the SIS100 feed box is in preparation for 2025.

Figure 77: Super-FRS local cryogenic assembly of transfer line, feed box, end box and jumper connection to the magnet, installed at the STF

The FAIR Cryo Plant CRYO2 (German GSI In-kind)

After the mechanical completion of the big central Cryo plant CRYO2 to FAIR in August 2023 including the installation of the cold box and DB3 (see Figure 78) and the compressor system (see Figure 79), six 100m^3 helium tanks were erected in spring 2024 (see Figure 80) and filled with 10.000 m3 of helium at approximately 17 bars required for the commissioning of the cryo plant. Currently the medium voltage distribution for the compressors is finalized for start of commissioning in 2025.

Figure 78: Cold box and DB3 installation after mechanically completion

Figure 79: Compressor system for CRYO2 and CW

Figure 80: Erection of the first 6 helium tanks

The Cryogenic Distribution System

The Cryogenic Distribution System is divided into three major lots: the SIS100 distribution system, the north/south transfer line including DB2 supplying also CBM / HADES and the Super-FRS distribution system.

In 2024, the last 28 bar pressure test was performed for the SIS100 distribution system Figure 81, which is now ready for cold commissioning.

Figure 81: Part of the distribution system in niche 5

The Super-FRS distribution system

The Super-FRS distribution system contains out of a long transfer part between the DB3 and DB2 and a transfer line between the Super-FRS branch box and the G branch (GLAD, high-energy branch). Both transfer lines and the DB2 itself were specified in 2024 and put out to tender on the market.

The complete Super-FRS distribution system is thus contractually bound and currently in the design phase. Installation will start in summer 2025 and will take around one year to complete. Figure 82 shows part of the Super-FRS distribution system, in particular the link from the DB3 in the North to the DB2 near the target region of the Super-FRS.

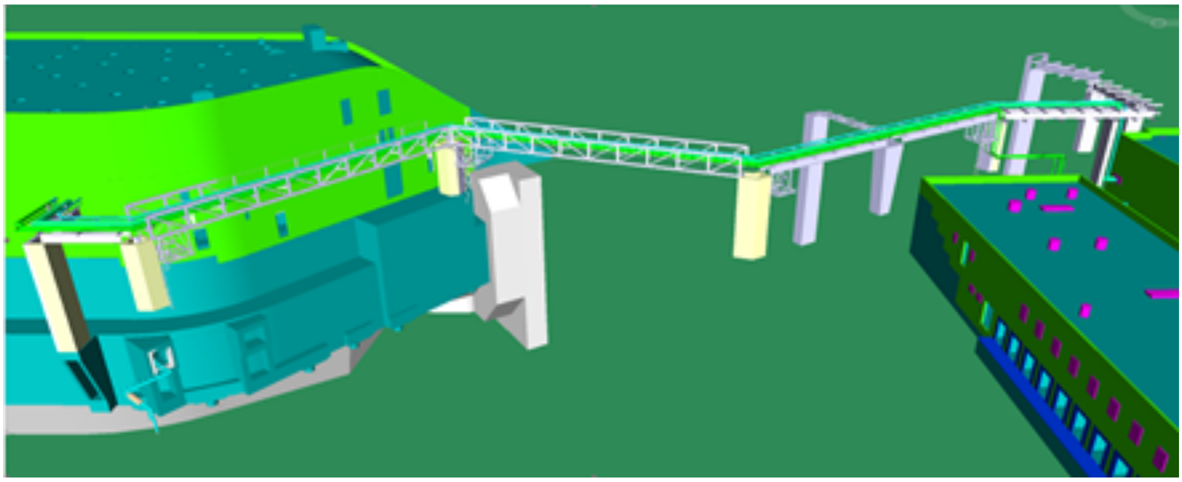


Figure 82: Cryogenic north/south connection to supply the Super-FRS and CBM

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 provided regularly to Fair Site & Building (FSB) for the processes of cable routing and 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 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 2024 in coordination with the machine installation. Up to now approx. 470km (5500 cables) were laid. Moreover, the design of the machine trays is finished for HEBT and for SIS 100 and the completion Super-FRS areas/buildings is expected in Q3/2025. The call for tender of the installation of machine trays, assembly and connection of user cables has been finalized in December 2024 and the company Electricity EOOD has also been contracted for this work package. The first order of material was placed in Q1/2025 and the first installation is planned for Q2/2025. Finally, the in-kind delivery of approx. 930km IT cables from the Indian Company Siechem Technologies Pvt. Ltd. was completed in 3 batches in 2024.

High Energy Beam Transport (HEB)

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

In 2024, activities for the high energy beam transport system (HEBT) were characterized by processing of ongoing procurements, re-procurement of ex-Russian components and the preparation of pre-assembly and tunnel assembly in close collaboration with the sub-project Site Management (SMG).

Twelve assembly groups of beam line section T1S2 were transported into the tunnel G0702A and positioned on the blue line. Due to ongoing building settlements, the assembly groups were not fixed to the floor and not adjusted in height. This will be done during the next installation phases in 2025 when the downstream sections towards Super-FRS and the upstream section towards GSI will be realized. With regard to the HEBT relevant areas in the northern FAIR buildings, main activities for HEBT were to track the installation of the technical building equipment in accordance with the planning. Furthermore, the detailed planning for the commissioning of HEBT Early Science and of First Science sections has started.

Magnets

The year 2024 was largely shaped by the design phase for the re-procurement of the remaining required magnets within the First Science Scenario (5 dipole, 39 quadrupole, and 14 corrector magnets). Mid-2024, the magnetic designs for the two dipole, three quadrupole, and two steerer magnet types had been successfully completed. The finalization of the mechanical design of magnets and stands is expected by mid-2025.

Magnet production began with the steerer magnets at the German supplier Partzsch and the dipole magnet dip17_0 at the French supplier Sigmaphi. By December 2024, half of the procured steerer magnets were delivered to GSI, the shipment of the 1st dip17 is scheduled in April 2025. In parallel, the quadrupole production has also started at Sigmaphi with yokes and coils for quadrupoles Q2 and Q11 under manufacturing.

Meanwhile, pre-assembly activities have continued. Nine quadrupole assemblies have already been transported into the tunnel, and additional 25 units are ready for installation in 2025.

Power Converters

The power converters for HEBT quadrupole and steering magnets are mainly built by the Indian company ECIL (Electronics Corporation of India Limited). In 2023, three three-party-contracts between FAIR, the Indian shareholder BOSE institute and the provider ECIL comprising in total 252 power converters for HEBT (159 for quadrupole and 93 for steering magnets) were closed.

Meanwhile, all power converters are manufactured, successfully tested and shipped to FAIR.

The series production of 53 power converters for dipoles and 8 power converters for quadrupoles by the company Jäger Elektrotechnik GmbH (Germany) is ongoing. So far, 40 power converters for dipoles (14 types) and all 8 power converters for quadrupoles (2 types) have been tested and delivered to FAIR. Due to their large power and size, the remaining 13 pulsed power converters will be connected to the 20kV supply system and will have to be assembled directly in the building. The associated 20kV transformers for these converters were delivered. 7 transformers were already installed in building H0719A. In Q2/2025 the assembly of the corresponding power converters inside the building can start.

The installation of all 45 power converter racks in building G0704A and all 144 power converter racks in building H0719A is planned to be completed in 2025.

Vacuum chambers

In 2024, the focus was on the re-procurement of the missing vacuum chambers for HEBT.

Chambers for quadrupole (except special quadrupole chambers) and steerer magnets, in total 125 pieces for Early Science and First Science, 309 bellows and 37 pumping chambers were manufactured by the Italian company SAES RIAL VACUUM. Their delivery and final acceptance are completed in the beginning of 2025.

After finalizing the design, material procurement and welding tests by GSI, the production of the rectangular dipole chambers with 12 pieces for Early Science and First Science, started at Fantini (Italy) in November 2024. Fantini scheduled the delivery of the last chamber for end of June 2025.

The GSI design office finalised the chambers' design of the remaining beam line tubes and a set of special quadrupole chambers (branching chambers, chambers with oval cross-section) for First Science and First Science Plus. Two joined calls for tender by FAIR and the Nuclear Physics Institute of the Czech Academy of Sciences are published at the beginning of 2025 for procurement these components.

Special Installations

First HEBT Special Installation assembly groups with diffusors, which are constituents of the Personnel Access System (PAS) of FAIR, have been assembled for upcoming beamline installations.

The FoS HEBT18 beam collimation system was delivered by the Italian company COMEB S.r.l and successfully tested at GSI. The full delivery of the HEBT18 and HEBT100 series products is scheduled for 2025 and 2026 respectively.

Moreover, the specification of the HEBT charge stripper is released and procurement can start in 2025. The graphite cores for the two HEBT Beam Dumps, located in the SIS100 injection and SIS100 extraction beam line, have been installed on site.

Special Stands

The FDR of the large support frame in building H0705A manufactured by Kraftanlagen Heidelberg GmbH was completed in December 2024. Production start is planned for Q1/2026 in order to install the large support frame in summer 2026 in compliance with the overall HEBT installation plan.

GSI Mechanical Integration Team completed the missing draft 3D-models and specification drawings for the modular stands of the second contract, that were handed over to BLEICHERT in September 2024. In the meanwhile, BLEICHERT completed the design phase and started the production. The delivery of these frames is expected for June 2025.

The design of the overall vacuum stands is under responsibility of GSI's design office. In 2024, all vacuum stands for the stage Early Science were designed and finally produced at the Spanish company Nortemecanica and the German company Baumann MV. In the meantime, all stands for Early Science are delivered. The finalization of the design for the stage First Science is planned for September 2025 with a production start in early 2026.

Vacuum Systems (VAC)

Authors: Dr. Maria Cristina Bellachioma, Dr. Andreas Krämer on behalf of the VAC department

In 2024 the procurement and delivery of vacuum standard components for the FAIR project have continued. A contract was signed for the production and delivery of radiation hard pre-pumps with the Italian company Agilent Technologies. The first units have already been delivered in 2024, while the remaining ones will come in early 2025. Another contract for non-radiation hard pre-pumps was closed with Leybold GmbH, the delivery will start in 2025. Regarding the gauges from Inficon AG, angle and gate valves from VAT Deutschland GmbH and turbo molecular pumps from Leybold GmbH, their delivery has continued. In addition, mobile pumping stations and leak detectors, which will be used during pre-assembly and vacuum tests at installation in the FAIR tunnels, were procured.

In total about 600 of these standard components with a market value of ~7.7M€ arrived in 2024 at FAIR/GSI. For all these components incoming goods inspections and logistics were expedited and the required documentation was produced and released in EDMS to be ready for installation in time.

Also, in 2024 the work on the vacuum control system has been continued. For the beam vacuum system, the electrical design of the PLC cabinets was finalized together with our Slovenian In-kind partner COSYLAB and the GSI Industrial Control team. While all cabinets were produced and delivered by the Slovenian company INEA, the SCADA software was delivered by COSYLAB. In addition, INEA manufactured the “Schützsteuerungen,” which will be used to control the permanently installed pumping stations for the beam vacuum system. The contract for “Schützsteuerungen” for the isolation vacuum system was awarded to the German company Bucher Automation. Production and delivery were finished in 2024.

Beside these the detailed planning of the combined PLC-controller racks for the isolation vacuum system was finalized. They will be produced by the German company Franke + Pahl. The FoS (First of Series) will be ready for FAT end of May 2025.

In parallel, the list of required cables was updated as prerequisite that the procurement, routing and laying of the cables could continue. In this framework the cable routing had to be checked and each cable to be officially released for laying. To cope with increased length requirements due to routing conditions, additional test with 200m long cables for two different types of ion gauges were done. For extractor type hot cathode gauges (Leybold IE514) we could successfully find adaptions of the cable parameters, that ensure to operate these gauges in the low UHV regime with very long cables. For cold cathode gauges type MKS 422 it could also be proven that these gauges are operatable with the long cables.

Moreover, the vacuum laboratory worked intensively to perform vacuum acceptance tests to all the necessary components for both the GSI (ESR, Cryring, SIS18 and Unilac) and FAIR (HEBT, Super-FRS, SIS100) accelerators machines.

For the High Energy Beam Transfer lines (HEBT) of FAIR Early Science, 69 vacuum chambers with a length varied from about 100 – 6600 mm (total length of all chambers ~130m) were produced in-house by the GSI mechanical workshop. After UHV cleaning, vacuum acceptance tests as part of FAT and SAT were conducted at GSI's UHV laboratory. Full vacuum acceptance tests were carried out for every single chamber, which include: visual inspection, He leak detection, outgassing rate measurement and residual gas analysis. To cope with the deadline given for the HEBT pre-assembly and HEBT installation into the FAIR Tunnel, five vacuum measuring systems were designed and commissioned and simultaneously and constantly operated.

Parallel to the in-house production chambers, full vacuum acceptance testing was also conducted on chambers and bellows made for HEBT and for SIS100 by the Italian company "SAES RIAL Vacuum". In addition, about 10 pre-assembly groups for both HEBT and SIS100 were mounted, vacuum tested and prepared for tunnel installation and are now ready to be dispatched in upcoming installation windows.

Throughout the year, a full vacuum acceptance test for a Super-FRS detector and its single components were also carried out.

In addition, VAC department has invested a great deal of efforts in maintenance and shutdown works for the vacuum systems of GSI's existing accelerators. Several vacuum sectors in SIS18, HEST, UNILAC, and CRYRING were vented and baked out, while at the same time pumps and other aging vacuum equipment was replaced by new ones. In order to keep and upgrade the performance of the GSI accelerators more powerful vacuum pumps were bought. 72 new ion getter pumps were bought for UNILAC, which will be installed during the next shutdown periods. Furthermore, various NEG cartridge pumps by SAES getters were purchased. Depending on the needs, these will either replace old Titanium sublimation pumps or will be installed to provide additional pumping speed in the ESR, SIS18, and CRYRING.

Consequently, these measures will significantly improve the vacuum performance of these machines.

Selected publications of 2024

[1] R. Niedermayer Philippand Singh, "Excitation signal optimization for minimizing fluctuations in knock out slow extraction," *Scientific Reports*, vol. 14, no. 1, p. 10310, May 2024, doi: 10.1038/s41598-024-60966-y.

[2] T. S. *et al.*, "Final design of the cryogenic current comparator for FAIR," in *Proc. IPAC'24* - 15th international particle accelerator conference, no. 15. JACoW Publishing, Geneva, Switzerland, May 2024, pp. 2311–2314. doi: 10.18429/JACoW-IPAC2024-WEPG42

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 operating, maintaining and developing the GSI accelerator complex. This is one of the world's leading accelerator infrastructures for nuclear physics and its many applications in fundamental research on matter, oncology, radio-biology, materials and high-density matter, amongst others. Our responsibilities include the ion sources from which all of our beams originate, the UNILAC linear accelerator, the high energy transfer lines HEST, the Experimental Storage Rings ESR, the CRYRING@ESR facility and HITRAP. We operate and organise the main control center from which we control all accelerators on the GSI/FAIR campus.

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. In 2024 the Galvanic workshop was successfully commissioned; it passed its formal certification process and a first Alvarez2.0 tank was copper coated with excellent quality.

The staff of our division provides the resources for operating and developing our facilities, including filling various mandatory roles of machine coordinators and safety responsibles.

Safety Record

The safe operation of our facilities is the highest priority in our work. The year 2024 had an impeccable safety record without any safety incidents. This demonstrates the outstanding level of expertise, care and discipline from our staff.

Budget and Procurement

During the year 2024 an additional budget of 5.4 M€ became available for our division from the SBM's. The various departments started an extraordinary procurement effort addressing some long-standing investment needs and, where possible, advancing future procurements. Amongst others, various new workshop machines, a new brazing oven, a stock of isotopes for future physics runs and a large quantity of spare accelerator parts were procured.

Physics Run 2024

The Physics Run in 2024 started on 9 Feb 2024 and ended on 27 June 2024. After its completion our users expressed full satisfaction with the delivered quality of the ion beams. The availability of beams for users ("beam on target") had been 75% of the scheduled time, slightly up from 74% in 2022. This increase is an important improvement but we still work on achieving our target of 80%. On average 2.8 experiments were served with ion beams in parallel, also slightly better than in 2022 when this number was 2.7. We have achieved the most productive GSI week ever from 21 May 2024 to 28 May 2024. During this week we delivered 800 hours of integrated beam time to up to 7 experiments who took data in parallel. The results and achievements were discussed and summarized in the Beam Time Retreat 2024 which took place on 11 and 12 July 2024 in Kranichstein close to GSI. Slides and summaries are available at: https://indico.gsi.de/event/18781/overview

Shutdown 2024

The shutdown 2024 started after the end of the physics run and was performed successfully. The subsequent beam time in 2025 was started on time and with good performance.

Accelerator Upgrade Projects

The accelerator upgrade projects made very good progress. The new gas stripper in the UNILAC was used in routine operation, much ahead of its planned rollout. Important operational data was collected and will be used for the optimization of this device. We applied with the GSI supervisory body for the next financing of 4.9 M€ within the Post-Stripper Upgrade project. The requested budget, within the overall agreed project plan of 35 M€, was approved and the Post-Stripper Upgrade project proceeds at full speed. The additional budget also supports the supply of drift tubes for copper plating at CERN. The UNILAC control system upgrade to FAIR standards was successfully tested in Autumn 2024 and is on track towards full readiness for operation from the Future Control Center FCC in the middle of 2026.

Figure 83: The Beam Time Retreat 2024 took place on 11 and 12 July 2024 in Kranichstein close to GSI.

POF Evaluation

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

In February 2024 we started a new performance committee at GSI. The mandate had been agreed with various committees inside GSI and FAIR and had also been presented to the FAIR MAC at the end of 2023. Participants come from all accelerator-related areas inside GSI accelerator operations and development but also inside the FAIR project. Representatives from the neighboring universities in Darmstadt, Frankfurt and Mainz are invited regularly and some on a case-by-case basis. The committee is reviewing the state of the various accelerators, is defining key performance indicators, is specifying their implementation and is establishing a technical roadmap of the GSI accelerator complex. The technical roadmap lists recommended actions over a time horizon of 30 years. The actions are defined to ensure ion beams for Super-FRS and SIS100 with high availability, specified intensity, sufficiently small emittances and the requested temporal rates.

A first sketch of a technical roadmap for the GSI accelerator complex has been established. The Performance Committee review of beam readiness for FAIR has been highly encouraging. For all foreseen types of ions the GSI facilities are today performance-wise fully ready for FAIR beam commissioning. Concerning ultimate ion beam intensities for FAIR: the required beam performance is available today for various types of ions. The most difficult case (U^{28+}) misses a factor 5 to the ultimate FAIR performance goal. The upgrade path in the technical roadmap addresses this present limitation and defines how ultimate performance will be established also for this ion type.

The sketch of the technical roadmap for the GSI accelerator complex has been presented to the Joint Scientific Council JSC and the FAIR MAC in 2024. Feedbacks have been highly supportive and the detailed technical roadmap is being completed during 2025.

The performance committee is strengthening the collaboration with the neighbouring universities at Frankfurt, Mainz and Darmstadt, but also reaches out to possible collaborators at Jülich, Aachen, Heidelberg (HIT) and Karslruhe (KIT). The technical roadmap will define detailed collaboration topics and such will strengthen our critical mass for advancing physics and technology in accelerators for nuclear physics.

Supporting and Preparing FAIR

Our division supports ongoing high-priority work on FAIR. Activities include:

- Machining of FAIR components at the GSI mechanical workshop in our division.
- Review and steering of the FAIR control system, including leading the project of the UNILAC controls upgrade.
- Leading the commissioning of FAIR. The first commissioning workshop for FAIR was organized on 7-8 November 2024. To ensure integration of GSI and FAIR operation, the head of GSI operation has also been appointed head of FCC commissioning.
- Preparation of the GSI accelerator complex for FAIR beam operation, including a clearly defined and agreed technical roadmap, as described in the previous section.

11.2 Accelerator operation

Activities of the Operation Cost Working Group

Head: Ralph Aßmann

Author: U. Weinrich

Structure of the OCWG

The Operation Cost Working Group (OCWG) was established by the FAIR Management Board to generate and present input concerning FAIR Operation and Commissioning towards the FAIR bodies. The working group was established in Summer 2023 und terminated its work with the input and presentation to the FAIR Council meeting in Summer 2024. The group was headed by U. Weinrich from the business area Accelerator Operation and Development with C. Tränkner from the division Corporate Controlling as deputy. All managing directors as well as experts from the different areas were part of this group.

Outcome of the OCWG activities

The main focus in the first half of 2024 was to scrutinize the data set generated in the second half of 2023 and to generate and transmit the final report. The final report was submitted on the 26th of April 2024. The main outcome were yearly operations costs (in 2024 prizes) of 262.7 Mio. € for the First Science Scenario (FS) and 280.1 Mio. € for the First Science plus (FS+) Scenario. For the official FAIR Commissioning phase from 2024 to 2028, a ramp up scenario (FS) consisting of 5.9 M€ (2024), 43.15 M€ (2025), 93.85 M€ (2026), 190.09 M€ (2027) and 268.24 M€ (2028) was derived from the FAIR Commissioning schedule. The cost categories ACC, Research & Experiments, Computing, Technical Infrastructures, Management & Administration and Energy were proposed for the budgeting and cost accounting purposes. For these categories the yearly commissioning costs for the years 2024 to 2025 were calculated. Finally - in order to support the FAIR shareholder decisions - the corresponding shares of each shareholder were calculated on a yearly base for the FAIR Commissioning Phase and the operation costs.

Reception by the FAIR bodies

In addition, presentations in the FAIR bodies Cost Scrutiny Group (CSG), Administrative and Finance Committee (AFC) and FAIR Council (seven meetings in total). The CSG made a deep dive into the methodology used for the calculation, compared the results to other accelerator centers and fully supported the outcome of the OCWG. Based on the input of OCWG and the CSG, in May 2024 the FAIR AFC formulated a recommendation to the FAIR Council to decide on the 2025 commissioning budget as presented and to establish a yearly process for the years to follow. Finally, in July 2024, the FAIR Council decided to follow the FAIR AFY recommendation.

In conclusion, one can say that the OCWG successfully paved the way for the FAIR bodies towards a proper financing of the FAIR Commissioning phase and a general acceptation of the volume of yearly FAIR operation costs.

Beamtime Report, Operations & Availability

Head: Dr. Stephan Reimann (GSI & FAIR)

Authors: M. Vossberg, O. Geithner

Operation

The beam time in 2024 began on January 15th with RF conditioning. In parallel, there was a dry run as well as commissioning with and without beam. At the end of the commissioning block, shifts with operator training took place, during which the subsequent physics experiments could also be set up. The physical run time for 2024, within the framework of FAIR Phase 0, was planned for 102 days and began on February 7. The beam time ended on June 28 and included 16 days of machine beam time. The machine beam time was divided into two blocks and mainly used for machine studies and testing specific beam parameters. During the beam time, a total of 12 different ion types with varying energies and charge states were accelerated and made available to 62 different experiments. The beam time started with a dual beam operation. There was argon beam from the EZR source for the UNILAC experiments in X0, X6, Y7, and M1-3; in parallel, there was carbon beam, followed by oxygen beam from the high-current source for experiments at the ESR and the caves HTA, HTC, HTM, FRS, and HAD. At the end of the first block, titanium beam from the Penning source was added for experiments X8 and Y7. This was followed by an approximately 25-day gold block. Gold was produced in two different ion sources and delivered according to the requirements of the experiments. The main user was the HADES experiment, while the CryRing could also be supplied via the ESR as well as HTA and HTD. At UNILAC, there was gold beam for X0 and materials research in the M branch. Due to staff shortages, no experiments were offered during the Easter holidays. To maintain the conditioning level of the accelerator facility, the UNILAC RF stayed in operation. This time was also used to carry out minor repairs and maintenance, and training shifts were conducted to prepare for the upcoming planned experiments. After Easter, there was a block in which X0, X8, and M1-3 were supplied with argon and iron beams; in parallel, there was iron beam for ESA experiments and HTA, and argon for commissioning of HITRAP. Additionally, for the first time, erbium beam was accelerated at GSI during this block. The experiment at FRS was able to receive this beam under stable conditions and high intensities. In May, experiments X7, Y7, and Z6 were supplied with chromium beam from the southern source. In parallel, there was nickel for HTD and, for the first time, molybdenum for FRS, HHT, and ESR. At the end of the beam time, there was a 43-day-long uranium block. To achieve a stable uranium level within the accelerator facility, it was necessary to condition the UNILAC RF for two days. The uranium beam supplied X6 behind the UNILAC and FRS, HHT, HTA, HTD, and ESR. Additionally, internal experiments at CRYRING with lithium, deuterium, nitrogen, and neon beams were conducted during this time.

The beam time planning was improved through dedicated setup times and longer blocks with the same ions. In addition, the consideration of parallel operation and compatible experiments was optimized. Better and more detailed documentation in the OLOG and CryRing operations also contributed to efficiency. The cooperation between the shift crew and the machine team was improved and the good preparation of the SIS18 patterns by the machine team contributed to the improvement. In addition, the control system was stabilized, which made for much more stable operation. The various requirements of the experiments led to a very busy beam schedule with an average parallel operation factor of about 2.8 (Figure 84). This required constant new settings and adjustments to the machine, especially in the period from late March to late June. 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.

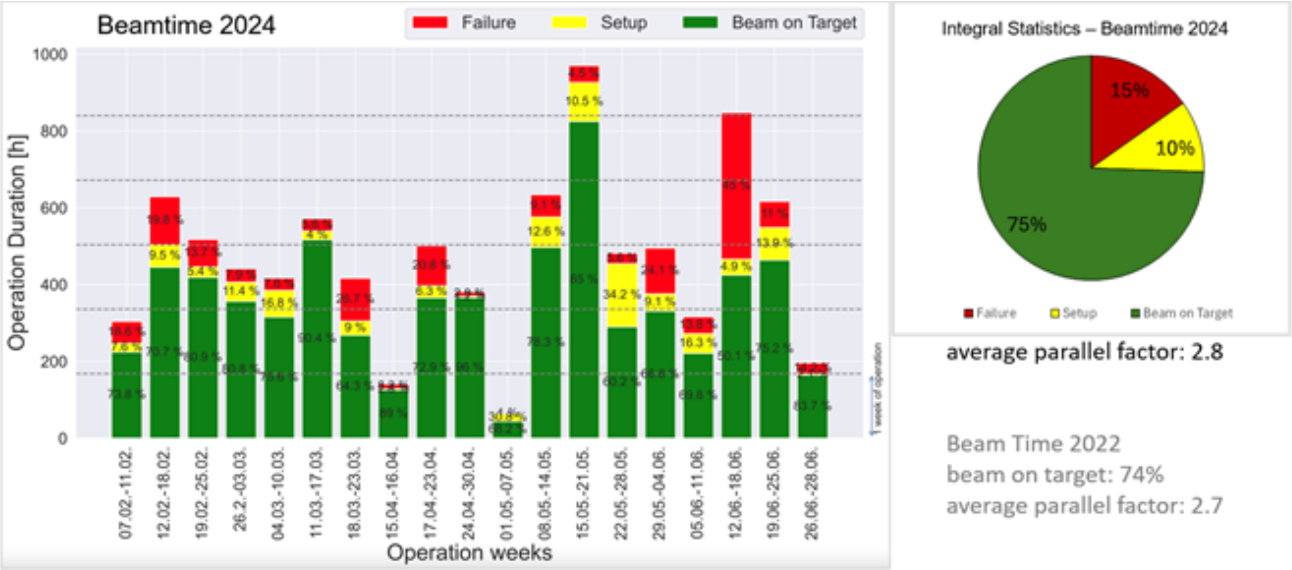


Figure 84: The diagram (left) shows the different event durations during the experimental beam time 2024. Each bar represents a period of one week, starting from the date shown on the x-axis and ending on the following Sunday. The colors green, yellow and red depict beam on target, setup, and interruption 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 beam time is 2.8. The right picture shows the overall availability for the experimental beam time 2024.

Availability

The work of the availability working group was continued this year to further improve the statistical basis of failure statistics by assigning failures that occurred to the appropriate specialist groups and verifying their root cause. At the end of the beam time, each expert group discussed a summary of the failures in order to work out possible improvements. During 2024, the facility recorded a total operational time of 8940.14 hours, which is distributed as follows: beam on target 6657 hours, setup time 925 hours and failures 1357 hours. The parallel operation factor reached 2.8, slightly higher than the 2.7 observed in 2022.

This increase reflects a greater number of simultaneous experiments, which in turn raised the complexity of machine adjustments and operation shift management. The accelerator failures of single devices with highest impact on the beam time were: 115 hours caused by a defective high-voltage connector in septum GS04ME1E, 93 hours caused by defect 20kV filter in AEG power converters, 61 hours due to a blown IGBT in GTS1MU1 and 55 hours of downtime caused by thermally destroyed magnetic coil in YR07MP1E septum. Among the most frequent failures, which interrupted the beam on target time and required frequent operator interactions were: over 50 failures on SIS18 Ring HF cavities, totaling over 145 hours of downtime, 27 failures totaling 23 hours and caused by defective anode capacitor, aging issues and insufficient conditioning of UNILAC RFQ GUH2BR2, 34 times totaling 13 hours due to the defect interface card in GTS2QT13.

The Long Shutdown

Head: Dr. Stephan Reimann (GSI & Fair)

Author: M. Klich

General activities and boundary conditions

The 2024 shutdown period started on the first of July. In the first three weeks, the new control system at the UNILAC was tested as part of the Injector Controls Upgrade (ICU) Project. During the last week, the UNILAC tunnel was closed, and the RF system was activated. The second part of the ICU test started on the 21st of October and lasted for 3 weeks. During the last week of the testing, the beam was transferred from the source to the transfer channel using the new control system at the UNILAC. During the entire shutdown period, the renovation of the experimental hall (EH) was prepared, which included the labeling and removal of unused cables. This shutdown period was also used to replace and refurbish several fire dampers, which required the shutdown of several sub-distributions and ventilation systems. These activities will continue in 2025.

Machine Activities

The start of the shutdown activities at UNILAC was influenced by the dry run of the ICU project. The activities could start on the first of July and had to be interrupted for the test with the RF system because of water leak. Hence, the main task at the beginning was to repair a water leak at the HSI IH1 triplet GUH3QT3 that occurred at the end of beamtime 2024. During the repair, copper delamination was detected in the groove beneath the inner triplet and needed to be investigated, but tests showed no limitations due to this delamination. For the Alvarez A4, the plan was to replace the old RF coupling loop with a new one tailored for the new Alvarez cavity to standardize the design. Unfortunately, the cavity didn't behave as expected, and the old coupling loop had to be reinstalled. This anomalous behavior will be further investigated in the upcoming shutdown. At the beginning of the recommissioning of the machine in mid-December, a leak was detected at the HLI RFQ and required a quick intervention, which was completed in January 2025. During the entire shutdown period, several defective beam diagnostic components were repaired at various locations on the UNILAC.

According to the schedule, the main tasks at SIS18 were the replacement of the GS06DFV scintillator window (Figure 85) and the defective connector of the electrostatic extraction septum, which broke at the end of the 2024 beamtime. After the window was replaced and the first heating period was completed, a leak occurred in a vacuum chamber, which required repair and the vacuum section needed a second bake-out. Due to a late delivery of spare parts, the septum could not be repaired until December. During the shutdown, it was decided to install a cryogenic insert prototype in section S01. After venting the area, a leak into the adjacent section was discovered, and the section valve had to be replaced, and both areas had to be heated.

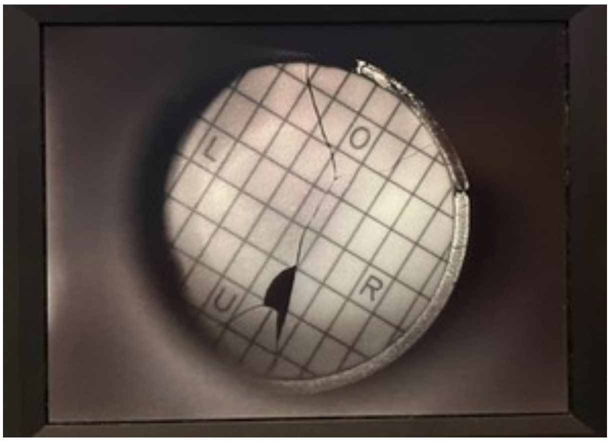


Figure 85: Damaged scintillator window GS06DFV (courtesy of: GSI/B. Walasek-Höhne)

In order to operate from the FAIR Control Center, the CUPID system in the High Energy Transport (HEST) area had to be upgraded. During this shutdown, several cameras were replaced and necessary cables were pulled. This upgrade will continue in the 2025 shutdown. At the end of beamtime 2024, Experimental Storage Ring (ESR) experts observed a stripper malfunction on the beamline to the ESR. This stripper hasn't been opened for many years, so this invention required detailed planning. After the necessary targets were produced, the repair of the stripper began at the end of September.

Among other things, new pocket drives and the electronic hardware for the stepper motors have been installed on the Fragment Separator (FRS). During the vacuum commissioning at the end of December, defective pumps were identified and will have to be replaced. This will be done in January 2025.

The two major activities at CRYRING@ESR were the replacement of the cathode in the electron cooler and the start of the installation of the new 14.5 GHz ion source. A very important task, the repair of the extraction septum, couldn't be completed due to delays in the delivery of spare parts. The repair will be continued in the first quarter of 2025.

During the beam time at HITRAP, problems were observed with the IH cavity, which were resolved in the shutdown through intensive investigation and performance testing. In November, a water leak was detected in the RFQ RF coupling loop and the repair will be completed in January 2025.

Outlook

The next shutdown period will start on 1 August 2025 due to the start of the renovation of the experimental hall and will be completed in the summer of 2026. There will be another ICU test at the end of the 2025 beam time, and the shutdown period will be interrupted by another test at the beginning of 2026. A high-impact activity will be the reinforcement of the shielding in the transfer hall.

Progress towards FAIR-Commissioning

Head: Dr. Stephan Reimann (GSI & FAIR)

Author: S. Reimann

Following a recommendation by the FAIR Machine Advisory Committee, a dedicated sub-project to prepare for FAIR commissioning was integrated into the FAIR project structure in 2021 and a corresponding team was formed. To benefit from synergies and experience, the sub-project and GSI operations team share the same management. The task of the sub-project is to plan, prepare and execute all accelerator-related commissioning activities from hardware commissioning to the first beam on target.

During the reporting period, the work of the commissioning team was mainly focused on preparing commissioning processes for the first hardware commissioning phases in close collaboration with work package leaders and system experts. Corresponding workshops continued and the processes for 11 out of 14 system types required in Early Science have now been developed and written down as workflow diagrams and dependency graphs. Subsequently, commissioning instructions and commissioning checklists are now being derived from these diagrams.

Machine / Subproject	Status of Preparation (processes & test procedures)
HEBT	40%
Super FRS	33%
SIS100	8%

Table 4: Progress of the commissioning preparation in terms of commissioning procedures and test automation. A value of 100% corresponds to a full set of commissioning instructions, commissioning checklists and the implementation of test sequences for an automated acceptance testing.

The FAIR commissioning schedule for the interim goals (early science, first science and first science+) developed in 2023 as part of the re-baselining process remains stable down to the section level. No significant changes occurred in the schedule.

The personnel required for commissioning related activities in 2024 was estimated at 8530 hours, which corresponds to 5.0 FTEs.

1st FAIR Commissioning Workshop

The first FAIR Commissioning Workshop took place on November 7th and 8th. All topics of machine commissioning from mechanical completion to commissioning with pilot beam were covered in 21 presentations. The main focus was on early science. Other subjects were the interaction between the machine installation and commissioning teams, the transition of safety and operational responsibility, the commissioning of the FAIR Control Center, the FAIR control system, technical building infrastructure and cryogenics.

External guests gave feedback and advice and reported on their commissioning experiences and lessons learned.

Figure 86: Participants of the first FAIR Commissioning Workshop (07.11. & 08.11.2024)

Project steering for commissioning of cryogenic plant started

The commissioning of the cryogenic plant "Cryo2" is the first of the major commissioning milestones of FAIR and is scheduled to begin in June 2025. The Commissioning team therefore started the project steering towards this date. An organizational project sub-structure has been developed accordingly. Detailed project schedule has been done containing all preparatory activities of construction, technical building infrastructure, cryogenics and safety. The plans are updated and reported to the commissioning team weekly. The first versions of important documents on safety aspects such as hazard assessment, designation letters, reporting processes for technical emergencies have been prepared.

As Cryo 2 is the first major FAIR commissioning activity, many processes, interfaces, responsibilities and safety aspects need to be clarified here for the first time. This will have a significant impact in all other areas in the course of the phased commissioning of FAIR.

FAIR Control Center

At the end of 2025, all accelerator operations will be relocated to the new fully digital FAIR main control room within the FAIR Control Center (FCC, presently under construction). Starting 2026, both the existing GSI accelerator systems and the first FAIR components will then be controlled from this central location. To achieve this goal, various work was carried out in 2024 e.g.:

- The integration of beam instrumentation and other major sub-systems of the GSI accelerators into the FAIR control system has further advanced.
- The Injector Controls Upgrade Project has made great progress in integrating the last remaining GSI accelerator, the UNILAC, into the FAIR control system architecture. It was shown that it is possible to accelerate and transport the ion beam using the FAIR control system only.
- The tender for the console equipment has started. The purchase is planned for Q1 2025.
- Various technologies for overview displays were evaluated in collaboration with the FZ-Jülich. The tender is due to start at the beginning of 2025.

Ion Source Operation at GSI

Head: Dr. Ralph Hollinger (GSI)

Authors: Ralph Hollinger, Aleksey Adonin, Aleksandre Andreev, Rustam Berezov, Michael Galonska, Fabio Maimone

The ion sources department provided in 2024 various types of ions for a physics run. 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 analyzed beam currents in front of the High Current Injector HSI-RFQ and of the HLI-RFQ, respectively.

The ECRIS was in operation to provide $^{36}\mathrm{Ar}^{8+}$ and $^{40}\mathrm{Ar}^{8+}$ ion beams for the commissioning and operation of the cryomodule CM1 of the HELIAC CW-Linac, for material research and machine experiments.

The Penning Ionization Gauge (PIG) ion source provided different ion species with sufficient performance and in stable operation. $^{56}\mathrm{Fe}^{2+}$ for material research, HTA, ESA and biophysics program, $^{52}\mathrm{Cr}^{2+}$ for NUSTAR groups (laser spectroscopy and super heavy elements) and for atomic and plasma physics application, $^{50}\mathrm{Ti}^{2+}$ was run for super heavy elements and $^{197}\mathrm{Au}^{8+}$ for material research.

Operation of high current ion sources (MUCIS-1990, CHORDIS and VARIS) from Terminal North was in general stable, high performance and without any issues. The whole block of 22 days of CH_3^+ operation was performed with a single source (MUCIS-1990) without any filament exchange. The maximum requested ion beam current in front of the HSI-RFQ was 2.0 emA. That allowed to achieve 0.6 emA of C^{6+} beam at the end of the transfer channel (TK), which corresponds to $6.3\cdot10^{10}$ particles within the 100 μs long pulse. Calculated average gas consumption for Methan operation was about 0.42 liters per day.

One of the important highlights of the beamtime 2024 was establishing of high current ^{170}Er beam for high energy experiments. The whole block of 11 days was stable and reliable operation of Er^{3+} from VARIS. The operation was performed using Er-cathodes made from natural material, containing 14.9% of ^{170}Er. With diligent optimization of the beam focusing in the LEBT as well as using the slits it was possible to get clear separation of $^{170}Er^{3+}$ beam in front of the HSI-RFQ, achieving 1.2 emA of the beam current that corresponds to $2.5\cdot10^{11}$ particles within the 100 μs long pulse. At the end of the UNILAC transfer channel it was reached 0.3 emA of $^{170}Er^{57+}$ beam current that corresponds to $3.3\cdot10^{9}$ particles within the 100 μs long pulse. The operation lifetime of a single Er-cathode was above 10 hours.

Another highlight was establishing of high intensity ^{100}Mo ion beam with VARIS. As for the Er case, for production of ^{100}Mo ion beam the cathodes made from natural Mo have been used. In spite of the fact that natural Mo contains only 9.7% of ^{100}Mo and a number of lighter isotopes lying in close proximity, it was possible to clearly separate $^{100}Mo^{3+}$ beam in the LEBT, reaching 0.5 emA in front of the HSI-RFQ. That allowed to achieve 65 eμA of $^{100}Mo^{38+}$ beam at the end of the transfer channel to the SIS18, which corresponds to $1.1\cdot10^{9}$ particles within the 100 μs long pulse. Stable pulse-to-pulse repetition as well as low intensity fluctuation during the beam pulse were achieved by using He as an auxiliary gas in VARIS. The operation lifetime of a single Mo-cathode exceeded 24 hours.

The longest block of 38 days performed with high current ion sources in 2024 was the uranium block. As a notable highlight the new record intensity of $^{238}U^{4+}$ beam of 14 emA ($2.2\cdot10^{12}$ particles in 100 μs pulse) have been reached in front of the HSI-RFQ.

Ion species	Duty cycle*	Intensity (RFQ/emA)	Ion source	Duration (days)
$^{36}Ar^{8+}$	CW	0.1	ECRIS	17
$^{40}Ar^{8+}$	CW	0.1	ECRIS	39
$^{50}Ti^{2+}$	10 Hz / 1 ms	0.04	PIG	5
$^{50}Ti^{2+}$	50 Hz / 5 ms	0.04	PIG	21
$^{52}Cr^{2+}$	50 Hz / 5 ms	0.14	PIG	14
$^{56}Fe^{2+}$	5 Hz / 1 ms	0.12	PIG	9
$^{197}Au^{8+}$	25 Hz / 3 ms	0.04	PIG	26
$^{15}CH^{3+}$	1.7 Hz / 0.45 ms	2.1	MUCIS-1990	22
$^{36}O^{2+}$	1 Hz / 0.5 ms	4.4	VARIS	6
$^{40}Ar^{+}$	2 Hz / 0.7 ms	9	CHORDIS	8
$^{58}Ni^{2+}$	1 Hz / 0.5 ms	3.3	VARIS	6
$^{100}Mo^{3+}$	2 Hz / 0.4 ms	0.5	VARIS	8
$^{170}Er^{3+}$	1 Hz / 0.45 ms	1.2	VARIS	11
$^{197}Au^{4+}$	1 Hz / 0.4 ms	3.8	VARIS	26
$^{238}U^{4+}$	1 Hz / 0.5 ms	14	VARIS	38

Table 5: Provided elements for the beam time 2024. *Duty cycle from ECRIS is always CW but the UNILAC provides in maximum 50 Hz / 5 ms

Activities of 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 2024 a substantial milestone was reached in the Division of Infrastructure Support as the refurbishment of the Galvanic workshop was completed. The plant has been successfully commissioned using a demo tank, and the first series tank of the Alvarez 2.0 project was Cu plated with satisfactory quality. The Cu plating of the large scale tanks is done in several steps:

- covering of all surface parts not to be Cu plated, such as outside surface, sealing surfaces, etc. by means of toluene-based varnish,
- removal of surface grease in a dedicated electrolytic degreasing bath,
- decapping by immersing in sulphuric acid to activate the surface before plating,
- electrolytic plating of an intermediate layer of Ni before the final,
- electrolytic Cu plating,
- completed by different rinsing processes between the different treating steps, and last but not least
- postprocessing of the surfaces by means of removal of cover layers (varnish) and polishing processes.

Especially the mechanical preparative and follow-up works, including the manufacturing of all anode setups necessary for all baths, are much more time consuming than the plating process itself which is at least in the order of one day.

GSI is well experienced in high-gloss high quality Cu plating and is the world leading facility for large-scale plating large-scale accelerator components and structures. The newly refurbished galvanic plant is now state of the art and fulfills all requirements with respect to environmental regulations and emission.

The Cu plating of the first series tank for the Alvarez upgrade of Unilac is an essential milestone. In Figure 87a the demo tank during commissioning of the galvanic is shown during the plating process. Figure 87b shows the first series tank in one of the different rinsing baths. Figure 87c shows the same tank after complete finishing together with the Alvarez and Galvanics team.

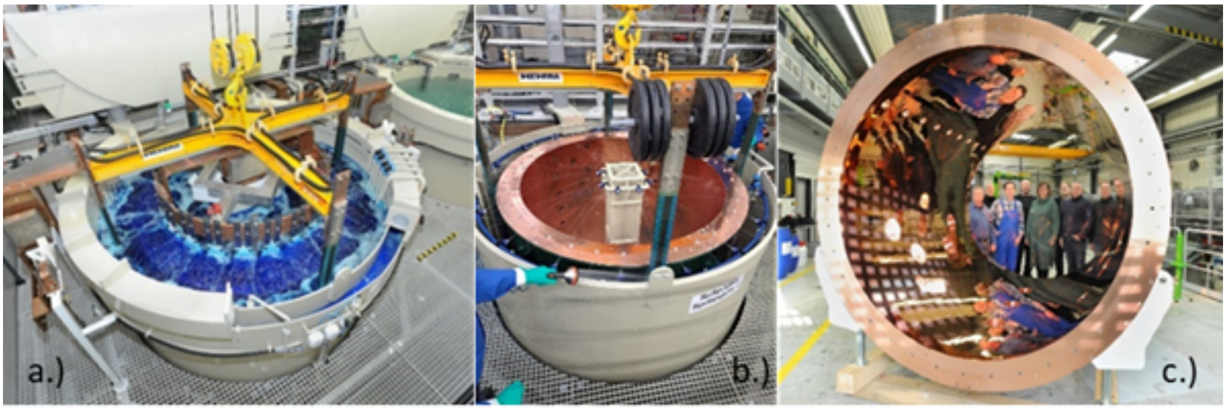


Figure 87: a) Demo tank during plating process in the galvanic bath. b) shows one step of the rinsing process of the first series tank and c.) on the right side shows the Cu plated series tank after all processing steps together with the responsible team.

For the upcoming years, the Cu plating the entire series of 25 tanks in total for Alvarez 2.0 upgrade of the UNILAC is scheduled. The processes will be done much faster when additional resources (area, personnel and dedicated investment) will be available to realize a parallel processing of the time consuming preparative and follow-up works on the tanks. This will speed up the project significantly.

Technology Laboratory Activities in 2024 for Campus Support

The Technology Laboratory supported lots of campus activities for running beamtime as well as for the preparation of the FAIR commissioning. To ensure the quality of the on-site installation, our new 3D Scanner was implemented and used. An example is shown in Figure 88a where the scan of a dedicated chamber has been successfully demonstrated on-site of FAIR.

One main activity in the technology laboratory is the use of our high-vacuum soldering oven. This oven is one of our work horses for different production processes, such as soldering and different types of temperature treatments. As our oven is now more than 40 years old with manifold technical problems, in 2024 we decided to order a new oven using a new technology developed for crystal growth. The new oven will be delivered by end of 2025, in the meantime we had some major repairs on the existing one. With the help of DESY we were able to finish some important production orders. An example is shown in Figure 88b.

In addition, a prototype for a specific detector drive unit for the Super-FRS was built up and tested in our technology laboratory, as shown in Figure 88c. The mounting of the series of Super-FRS drive units has also been started in the end of 2024 with ongoing activities. The work was performed together with the Super-FRS experts and includes different activities, such as assembly and adjustment of different components, vacuum tests as well as survey and alignment and final functional tests.

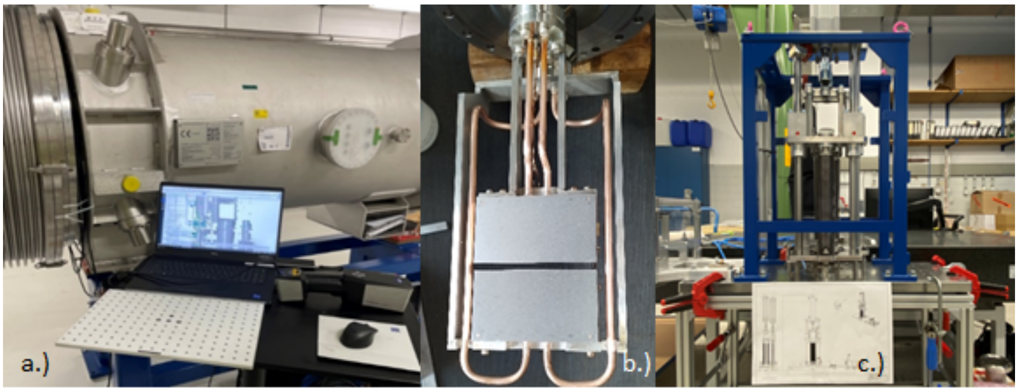


Figure 88: a) The figure demonstrates the use of our new 3D scan unit during the mounting of SIS100 components in the FAIR tunnel. b.) shows a beam diagnostic device for the GSI accelerators soldered by our colleagues with the help of DESY. c.) The right figure shows the prototype detector drive unit for Super-FRS.

To support the operation of existing GSI accelerators, different survey and scanning activities have been performed, e.g. the 3D scan of different coil geometries at ESR magnets. The aim was to develop a 3D model to initiate industrial manufacturing of a coil replica as spare part.

Activities of Mechanical Workshop and Metal Working in 2024 for Campus Support

For the Alvarez Upgrade Project the series welding of the static tuners has been started after successful welding tests. This is a longer-term activity for 200 pieces. As the desired length depends on the frequency behavior, it will be determined later on during rf-commissioning tests using dynamic tuners. After defining the right lengths, the system will be completed by a last welding step of the individual tuners. This whole procedure will last over the upcoming years until completion of the new Alvarez Poststripper 2.0.

For the existing Alvarez Post-Stripper spare drift tubes have been manufactured by means of recycling of already used components.

One main and highly labor-intensive activity in the Mechanical Workshop and Metalworking Department is the support of the SIS100 magnet installation on-site of FAIR by welding activities. To strengthen the team, two additional welders have been employed with 100% working on FAIR activities. For all welding activities on pressure vessels intense and regular training is essential. For that purpose, a separate welding laboratory was established to allow the training of the welders under conditions as realistic as possible. Main difficulties are the manual welding under hard physical constraints due to narrow construction space in the area of the different welding connections.

In parallel, the activities on the development of a special gun for orbital welding have been started to optimize the whole process with respect to series efficiency.

Besides the welding activities nearly the whole team is prepared to work on-site and to support the installation activities of SIS100, HEBT and Super-FRS in case of staff shortages. Furthermore, Super-FRS was strongly supported by manufacturing of drive units in the Mechanical Workshop, as shown in Figure 91.

In addition, the colleagues strongly supported an interesting project of development of miniaturized accelerator structures by means of 3D metal printing. The Cu printing was carried out by an external supplier and our workshop finished the structure. Some test effort was necessary to adapt the process to the material characteristics and the achievable precision.

Another remarkable project in the workshop was the purchasing of two new and innovative metal processing machines that are now available at GSI: a CNC-based lathe machine with integrated milling units and a CNC-based plasma-cutting machine. These machines are essential for upcoming manufacturing orders and significantly improve the possible production options.

The following figures give some impressions on our 2024 activities in the department of Mechanical Workshop and Metalworking.

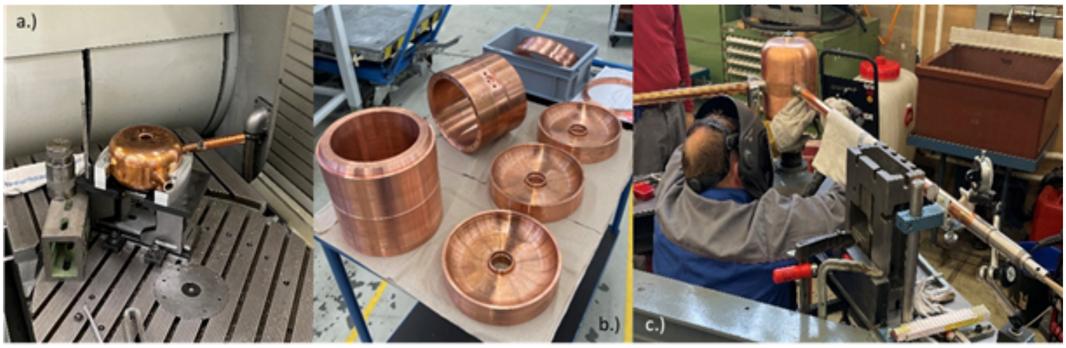


Figure 89: Drift tubes for existing Alvarez at UNILAC. Part a.) shows the repair of a leakage of the inner cooling pipe of a drift tube by means of soldering. b.) shows newly manufactured parts of a drift tube for Alvarez A I. The right panel c.) shows the welding of the stems of the A I drift tube.

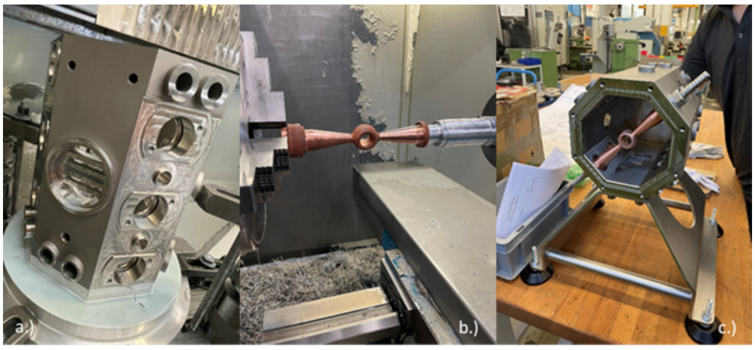


Figure 90: Development of miniaturized accelerator structures. Part a.) shows the 3D metal printed miniaturized tank during the drilling process to achieve the final dimensions with adequate surface quality. b.) shows the similar process for the miniaturized drift tube, while the right panel c.) shows the finally mounted complete structure.

Figure 91: Support of the FAIR project. a.) shows the drive units for Super-FRS, b.) show the orbital welding gun test placement, and c.) shows preparative work for the welding connections on SIS100 dipoles.

Figure 92: New machines in the Department of Mechanical Workshop and Metalworking. a.) shows the new lathe with combined drilling unit, b.) shows the plasma-cutting machine.

Operation and Developments of the Cryring@ESR Facility

Head: Dr. Frank Herfurth (GSI)

Author: F. Herfurth

In 2024, the low-energy storage ring CRYRING@ESR delivered several beams using both the local injector and the high-energy transfer line from the experimental storage ring ESR.

From the local source $^{16}O^{5+}$, $^{20}Ne^{+}$, $^{32}S^{3+}$, $^{2}H^{+}$, $^{15}N^{1+,5+}$, and $^{20}Ne^{7+}$ were provided for experiments in the ring. Unfortunately, the planned $^{6}Li^{3+}$ turned out to be too weak from the local ECR source. Although the produced amount of Li 1+ and 2+ ions could be considerably increased compared with earlier attempts in 2023, the intensity of 3+ was well below the required $1x10^{6}$

charges necessary for setting up storage and electron cooling. All other ions were delivered with intensities either well above or at least close to the intensity required in the experiment proposals.

The GSI accelerator complex, including CRYRING@ESR, was used to provide ^{197}Au ions in a beryllium-like charge state (75+) for two experiments. The newly designed transverse electron target could be tested successfully with the provided beam with intensities between one and ten million ions per ring filling. Unfortunately, the beam to the fixed target of the material research group had to be canceled due to a broken magnetic septum.

To analyze the availability and quality of the beam delivered to the experiments, a new approach to the analysis of some of the archived data was implemented. Firstly, offline, to define suitable views of the data but with the intention to create a permanent online monitor of beam availability. The figure below shows the results for the ^{197}Au^{75+} ion beam experiment with a beam transferred from the ESR.

Despite the extensive efforts that went into the vacuum system, the beam lifetime and background were not improved. Especially in the electron cooler section, this effect was prominent. The reasons for this are likely to be a too-short bake-out period not sufficient for the newly installed internal electrode structure and an extraordinarily hot cathode of the electron gun with some contact with the surrounding material. We used the shutdown in the second half of the year 2024 to inspect and solve those issues. The cathode was tested in a test stand and eventually replaced with a new one that passed the test before final installation. The bake-out was repeated using an extended period to make sure the complete inner structures got hot enough. The shutdown in the second half of the year was also used to refurbish the 14.5 GHz ECR ion source previously installed at Frankfurt University. Due to the higher magnetic field and hence higher electron cyclotron frequency and the larger volume of the ionization chamber, this source could deliver slightly higher charge states as, for instance, medium heavy tungsten ions at 7 to 12+. Unfortunately, the ready-built low-energy IPM could not be installed as tests revealed a non-working multichannel plate detector, and its replacement did not arrive in time for the final bake-out period.

In 2025, there is again extensive user operation planned. Additionally, the 14.5 GHz should come online towards the end of the year. Along with a finally working version of the low-energy IPM, the CRYRING@ESR facility shall be even better prepared to serve the proposed user experiments. Further strengthening the archiving of data and its analysis will also support this.

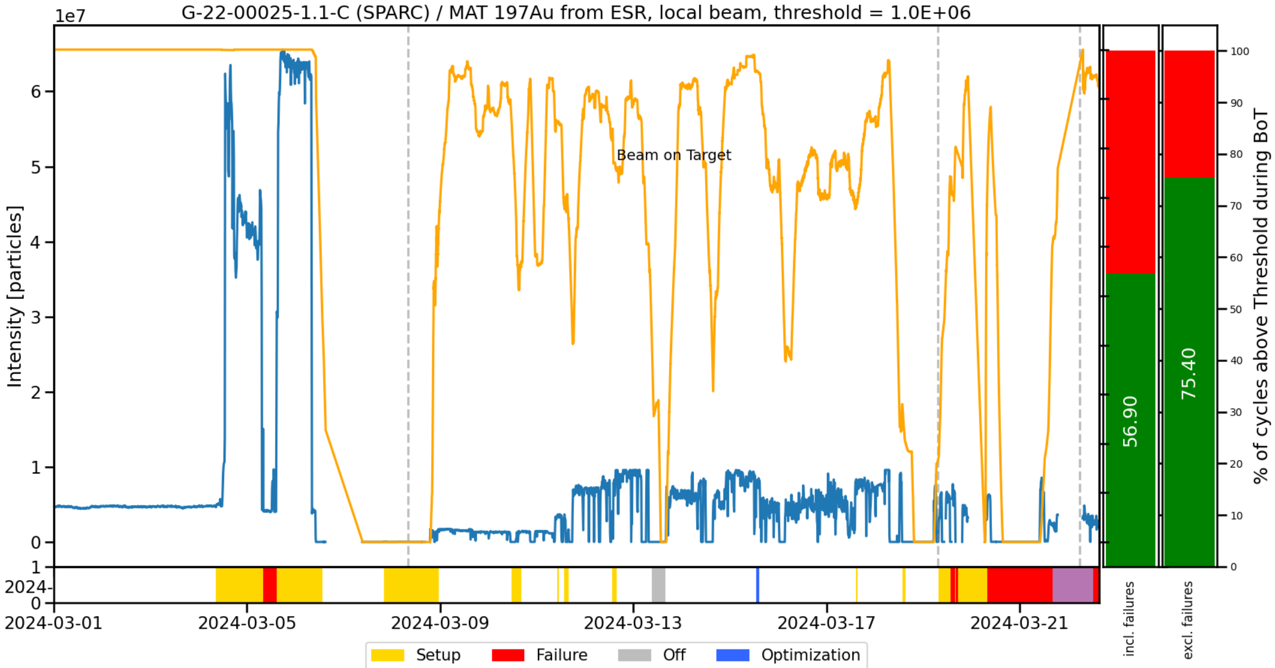


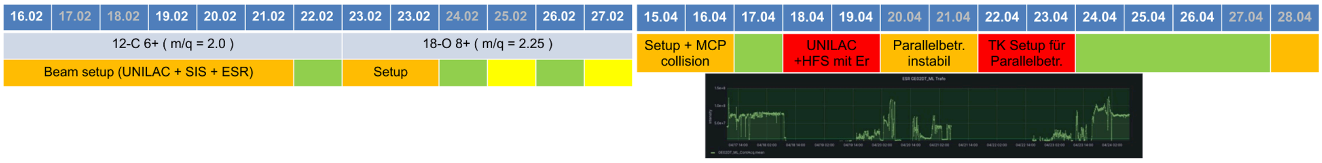
Figure 93: Accelerator availability plot. Shown are the ion beam intensity (blue line) on the left axis and the moving availability for 6-hour periods on the right axis (orange line). The availability is calculated as the fraction of ring fillings for which the ion beam intensity is above the proposal threshold (1 x10^{6} ions in this case) for 6 hours. Here, 100% means that for 6 hours, every ring filling delivered more than one million ions. Below the plot is the color code of setup, failure, and optimization periods as recorded in the operation's logbook (OLog). On the right-hand side, the integrated availability over the "beam on target" periods is shown, including all failures, setup, and optimization time without the failures. The plot starts on the left with ring setup time using a local D+ beam (100% available). Then, the GPAC experiment officially started on March 8th (left dotted line) and went on until March 19th. After this, a setup period for the following MAT experiment started. The availability for the MAT experiment period was low because of the broken septum. However, some availability was recovered by using the ring for machine experiments without the need for an extracted ion beam (violet period in the lower bar).

Commissioning Progress of the HITRAP deceleration and trapping Facility

Head: Dr. Frank Herfurth (GSI)

Author: Z. Andelkovic

The HITRAP deceleration facility has seen two beam time periods in 2024, both lasting about 12 days. The goal was to reestablish ion deceleration, identify and transport ions at 6 keV/nucleon from the RFQ to the Penning trap, and, eventually, capture, cool, and re-eject ions towards experiments. Except for beam cooling, which was performed on locally produced highly charged ions, all these goals were met.



16.02	17.02	18.02	19.02	20.02	21.02	22.02	23.02	23.02	24.02	25.02	26.02	27.02
12-C 6+ (m/q = 2.0)							18-O 8+ (m/q = 2.25)					
Beam setup (UNILAC + SIS + ESR)						🟩	Setup		🟩	🟨	🟩	🟨

15.04	16.04	17.04	18.04	19.04	20.04	21.04	22.04	23.04	24.04	25.04	26.04	27.04	28.04
Setup + MCP collision		🟩	UNILAC +HFS mit Er		Parallelbetr. instabil		TK Setup für Parallelbetr.		🟩				🟧

Figure 94: An overview of two commissioning beam times in 2024. The orange fields show beam setup periods, the yellow are periods of unstable RF amplitude, and the green fields show normal beam operation. The red fields indicate a beam interruption due to device failure anywhere in the accelerator chain. The graphic below shows the ion intensity at the ESR during the second period and correlates it with the availability chart (above).

The first commissioning block was separated into two distinct parts, which followed seamlessly after each other: one, with a fully stripped ^{12}C (m/q ratio of 2.0) and another with ^{18}O (m/q ratio of 2.25), as shown in the table below. The first period was largely occupied with the beam setup of the preceding accelerators so that only two shifts remained for the setup of HITRAP. They could be used to establish deceleration to 0.5 MeV/nucleon. The change of the ion species took about two days to propagate to HITRAP. A larger charge-to-mass ratio required higher amplitudes of the RF devices, which revealed an instability of the IH structure RF supply. Despite highly unstable conditions, it was possible to reestablish deceleration to 0.5 MeV/nucleon and transport the beam through the RFQ. Additionally, those shifts were very useful in identifying the necessary repairs and improvements. Eventually, we were able to remove a shortcut of an Einzel lens, change the screen behind the RFQ to enhance its sensitivity and find a provisional solution for a water leak from the inner triplet of the IH. Further analysis of this period's results led to the decision to use ^{36}Ar (m/q ratio of 2.0) for the next beam test, instead of the heavier ^{40}Ar.

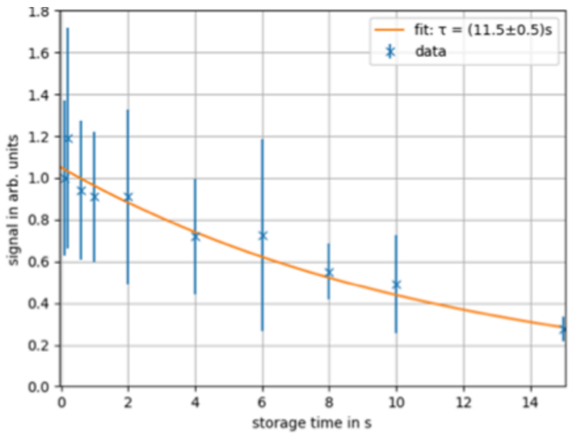


Figure 95: The relative intensity of ^{36}Ar^{18+} ions stored in the HITRAP cooling trap as a function of time. The exponential fit reveals a lifetime constant of about 11 seconds.

The second commissioning block started with a much faster beam setup. Unfortunately, after only one day of stable operation, an outage in UNILAC and problems with the parallel operation of argon and erbium beams led to about six days of no beam or unstable beam for HITRAP, as shown in the first figure. However, during the second half of the block, the stability increased significantly, and it became possible to reestablish both deceleration steps towards 6 keV/nucleon. The decelerated beam was transported through the low-energy beam line for the first time and identified both in front and behind the ion trap. Finally, the ions were trapped in the cooling Penning trap. This demonstrated HITRAP's ability to decelerate and trap accelerator-produced highly charged ions – a worldwide unique feature. The second figure shows the relative number of stored HCI as a function of time, revealing a storage time constant of about 11 seconds, sufficient for the envisaged electron cooling. The remaining beam shifts were used to further investigate the ion-trapping process, but unfortunately were not sufficient for the online demonstration of electron cooling.

The general GSI accelerator shutdown period was used to consolidate the unstable amplitude of the HF at the cavities and to continue the expansion of the FAIR control system at HITRAP. With several dry-runs and extensive refurbishment of the amplifiers, it was possible to reach the full 170 kW at the IH cavity and 120 kW at the RFQ cavity – sufficient for all charge states up to bare uranium. The control system was adapted to include warming pulses for both cavities at low amplitudes, which significantly reduces the risk of overheating at higher powers. Finally, new linear motors were added to all diagnostic elements after the RFQ, replacing the dysfunctional stepper motors. Electrostatic beam steering devices were added to the control system and prepared for the next year's beam time. During these works, the local EBIT remained in operation and was constantly used to verify the updated controls and detectors.

Outlook to the upcoming experiments

The results of 2024 demonstrate the feasibility of the planned experiments at the HITRAP facility, provided that the current commissioning engagement will be maintained. This holds especially regarding the observed deficiencies: the aging RF amplifiers and cavities, the replacement of the leaking inner triplet of the IH, and the adaptation of detectors for the identification and transport of slow ions, which all require sufficient resources, experienced staff, and extensive dry- and online runs.

In 2025 two PAC experiments were granted beam time by the General Program Advisory Board (GPAC). Both aim to irradiate crystal surfaces with slow HCI and investigate the formation of microscopic hilocs.

Selected publications of 2024

[1] Z. Andelkovic, et.al.: "Preparation of Low-Energy Heavy Ion Beams in a Compact Linear Accelerator/Decelerator," *Joint Accelerator Conference Website HIAT2022* (2022), doi: 10.18429/JACoW-LINAC2018-FR1A05.

[2] S. Rausch, "Deceleration and electron cooling of highly charged ions at HITRAP," PhD thesis, Tech. U. Darmstadt (2025), doi: 10.26083/tuprints-00028939

ESR operation in 2024

Head: Dr. Bernd Alfred Lorentz (GSI)

Authors: B. Lorentz, S.Litvinov, R.Hess, M.Steck, R. Joseph, U. Popp, J. Rossbach, C. Peschke

As reported in the GSI-FAIR annual report 2023, a long list of shutdown activities was executed in the long shutdown 2023. The shutdown for ESR was extended up to the foreseen start of beam operation in February 2024 because of delays caused by discovery of asbestos contamination from the 30-year-old heating jackets that were replaced at the dismounted electron cooler. Despite the delay caused by this, the ESR was put into operation in time for beam commissioning. The recommissioning of the remounted electron cooler, as well as the recommissioning of the as well removed and reinstalled electrodes of the stochastic cooling system posed no problems, and was executed in a few days.

The ESR beam operation time 2024 was with 109 days longer than the previous years, and covered the time from 17.02.-27.06., with a 3 week break around the easter holidays. Beam was delivered to 6 physics experiments, two at the CryRing@ESR facility, one at the HTA station and 3 internal to ESR. In addition, there were two blocks where beam was decelerated to 4 MeV/u and extracted to HITRAP for commissioning. In the following the different blocks are discussed in more detail.

At the beginning of beam operation, three periods of Deceleration of $^{12}C^{6+}$, $^{18}O^{8+}$, and $^{36}Ar^{18+}$. As these are ions of moderate mass and charge an ESR Injection Energy of 45 MeV/u was used, allowing the deceleration of the beam to the required 4 MeV/u in one ESR deceleration step. Setup times for the ESR deceleration and extraction were in the order of a day for the first setup ($^{12}C^{6+}$), and even less for the other ions. Here the progress in routine operation and performance of the LSA control system was very helpful, as the $^{12}C^{6+}$ setup could easily be adopted by just scaling the mass and charge for O and Ar ion operation.

For recommissioning of the stochastic cooling system after extensive work in the preceding shutdown, a 400 MeV $^{79}Au^{79+}$ beam was injected into the ESR. Despite several hardware failures, including a repair of the HV power converter of the electron cooler over several days, the recommissioning of the stochastic colling system could be executed, and the functionality of stochastic cooling in all three planes could be demonstrated. The stochastic cooling system is fully operational and can be used for subsequent experiments.

The Au beam from SIS18 was then prepared for experiments at CryRing@ESR. As the experiments requested Be-like Au^{75+} the injection energy was lowered to 65 MeV/u for efficient stripping, the beam decelerated to 12 MeV/u and extracted to CryRing@ESR.

Before switching to operation with Uranium beam, an experiment making use of the isochronous optics mode in ESR was executed. A $^{100}Mo^{42+}$ primary beam from SIS18 was used to setup the ESR. Then a production target in the transport line between SIS18 and ESR (TE line) was used to produce different elements/isotopes. $^{98}Mo^{42+}$, $^{98}Zr^{40+}$, $^{96}Sr^{39+}$ were injected into ESR and studied by the experiment.

The Uranium Block started with a channeling experiment with 192 MeV/u $^{238}U^{89+}$ at HTA. For this purpose, a 192 MeV/u U^{90+} beam was injected and stored in ESR. The U^{90+} ions pick up an electron in the electron cooler and thus have the right charge. Moving in a dedicated, moveable septum magnet in the ESR that only deflect the U^{89+} ions and not the still stored U^{90+} beam, the U^{89+} beam is slowly extracted and guided through the beam transport line to the HTA target station. Depending on the electron beam current in the electron cooler, a slow extraction in the order of $10^{-3}\ s^{-1}$ of the initially stored intensity is achieved.

Two internal experiments concluded the ESR operation in 2024. The first one aims at a Thorium beam stored in ESR. To accomplish this, a production target in the TE line is bombarded with Uranium beam, producing a thorium beam for injection into ESR. The intensity of the thorium is too low to setup the required ESR settings with stochastic cooling and stacking at 400

MeV/u, and deceleration. Therefore, the ESR setup is prepared with primary Uranium beams. Only when all the required settings are prepared, the production target is moved in, and the machine settings are scaled to the thorium ion properties. The setup procedure is complicated and time consuming. All the required steps were executed, and the beam handed over to experiment. Unfortunately, a failure of a netfilter in the 20 kV Transformer station, which couldn't be repaired in adequate time led to a cancellation of the experiment.

The netfilter repair could be concluded in time for the last experiment in 2024. A 300 MeV/u beam from SIS was stripped with a 100 mg/cm^2 Cu target in the TE line to provide a U92+ for ESR. The beam was injected, and decelerated to 17 MeV/u. The internal gas jet target in the ESR was run with Deuterium gas, providing the necessary interaction with the Uranium beam. Over two weeks of operation in this mode, an intensity of >5E7 Uranium ions were regularly delivered to the users. This is the highest intensity reached for bare uranium at low energies in ESR so far, certainly one of the reasons is the improved vacuum condition in the ring after the exchange of all ion getter pumps around the ESR in the shutdown 2023, but also the good performance of the preceding accelerator chain, and is promising for the future operation of the facility.

In addition to the physics experiments described above, during the two blocks dedicated to machine experiments several studies by different departments were executed. This included studies of the RRF department on the Barrier Bucket cavity system in the ESR, beam instrumentation (FCT, novel tune measurement), study of bunched beam measurements by a experimentalist group, studies on beam optics in the ESR, and finally some first measurements on an ongoing PhD work on the investigation of beam losses during the deceleration cycle in the ESR [1]. Some of the available machine experiment time was dedicated to the recommissioning of the electron and stochastic cooling systems reported earlier in this report.

Selected publications of 2024

[1] A.Sherjan *et al.*, "Machine Studies at the ESR," GSI PhD / Master Thesis Works Report 2024

UNILAC status report

Head: Uwe Scheeler (GSI)

Author: H.Vormann

In 2024 the UNILAC was in operation for 102 days of user beamtime, eight days have been used for operator training, 14 days for machine studies and 29 days for dry run periods. The dry runs were used for tests of the new UNILAC control system, including tests with beam. With 14 days of commissioning (incl. RF conditioning) before the start of the user beamtime the total operation time sums up to 167 days.

The beamtime started on 2nd of February with a three weeks block of Carbon beam (${}^{12}C^{6+}$), generated from Methane molecules CH_3 by the MUCIS (Multi Cusp Ion Source), and Argon beam (${}^{40}Ar^{10+}$) from the ECR (Electron Cyclotron Resonance Ion Source) in parallel, followed by two weeks Titanium beam from the PIG (Penning Ion Source), for the SHE experiments (${}^{50}Ti^{2+}$). After a short Oxygen block from the VARIS (Vacuum Arc Ion Source), a long period of gold beam followed from the end of February, lasting four weeks. Gold was delivered as high intensity beam (${}^{197}Ar^{4+}$ from the VARIS) for the SIS18 and as high duty cycle beam from the PIG (${}^{197}Ar^{8+}$, 25 Hz, 3ms) for the materials research at the UNILAC. A planned three weeks maintenance break during the Easter holidays was followed by one week Iron beam (${}^{56}Fe^{2+}$) from the PIG, a special Argon beam from the ECR for the HITRAP experiment behind SIS and ESR (${}^{36}Ar$, from the ECR, the lighter Argon isotope in order to meet the requested HITRAP beam quality) and 11 days of Erbium beam from the VARIS (${}^{170}Er$) – a new ion species at the UNILAC, provided for the first time ever. After a week of machine studies with Argon beam, a mixed block with Nickel from the VARIS (6 days), Chromium from the PIG (14 days) and Molybdenum from the VARIS (8 days) followed in May. The isotope ${}^{100}Mo$ was delivered for the first time from UNILAC (tested at VARIS ion source 2022). The Chromium isotope ${}^{52}Cr$ from the PIG was chosen as a substitute for ${}^{54}Cr$, which was originally requested from the SHE experiments: For technical reasons, ${}^{54}Cr$ would have had to be delivered from the ECR. The useful charge state 8+ could not be provided at the HLI-RFQ because the necessary RF field level was not reachable. On the other hand, operation with charge state ${}^{54}Cr^{10+}$ cannot provide the necessary beam intensity at the experiment. So, the SHE experts identified ${}^{52}Cr$ as a practicable isotope beam for alternative investigations. The ${}^{52}Cr$ beam block from PIG then turned out to be very successful. The beam intensities using natural material composition (83.8% ${}^{52}Cr$) was higher than the typical intensities of ${}^{50}Ti$ or ${}^{48}Ca$ used so far. The beam time finally continued with a five-week Uranium block from end of May on, including 7 days of machine studies, also with pulsed Hydrogen gas stripper operation. Within the machine studies again Uranium intensity records have been achieved, as 11 emA of U^{28+} at the gas stripper exit and 2.5 emA U^{73+} at transfer channel end, and even 24 emA of multi charge beam (U^{27+}, U^{28+} and U^{29+}) at the gas stripper exit, resulting in 3.5 emA U^{73+} at the end of transfer channel.

Commissioning of the CW advanced Demonstrator was performed with Argon beam from the ECR (three weeks in June).

The beam time 2024 was conducted with a pair of Alvarez quadrupole lenses out of operation, and with the partially damaged HLI in-tank quadrupole triplet UN5QT4 operated as a doublet (quadrupole UN5QT41 out of operation). Furthermore, the steerer magnets at the exit of the HSI-RFQ were out of operation, due to a water leakage. The pulsed gas stripper and the new explosion proof roots pump stand were used during the full beam time. Unfortunately, related with a few technical restrictions: The pulsed stripping gas valves had shorter durability 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.

Figure 96: View into IH1 with construction installation

The shutdown 2024 started in July with tests of the FOS RF coupler loop at Alvarez A4 (FOS = First of Series, Post Stripper Upgrade Alvarez DTL section). This RF coupler with a DN160CF vacuum flange had worked properly at the FOS, but in the new position at A4 the control of the RF amplifier suffered from an unstable frequency behavior. Investigation and optimization of system amplifier and loop will follow and should solve the problem.

Further extensive work was conducted during the shutdown 2024: A leaking water connector tube of the HSI in-tank quadrupole triplet UH3QT5 was repaired. Additionally, the opening of the cavity allowed the cleaning of the inner surface. A considerable amount of dust could be removed.

The cold resonance frequency of the HSI-RFQ was corrected by replacing a fixed tuner by a shorter one, besides that the RFQ was equipped with new turbo and ion getter pumps. New vacuum pumps have also been installed in the gas stripper and at a few positions at Alvarez Cavities. The Alvarez cavities A3 and A4 have also been equipped with new and reliable temperature control devices to prevent overheating of the quadrupole magnets.

As a spare part a new drift tube for Alvarez A2 (DR105) has been produced in house, with some external work (electron beam welding and copper coating). Finally, the pair of Alvarez quadrupole lenses was brought back into operation, as the suspected drift tube leakage had disappeared.

As a long term measure, a 10° dipole kicker magnet (used at the injection to the M-branch) has been ordered and delivered before the end of the year.

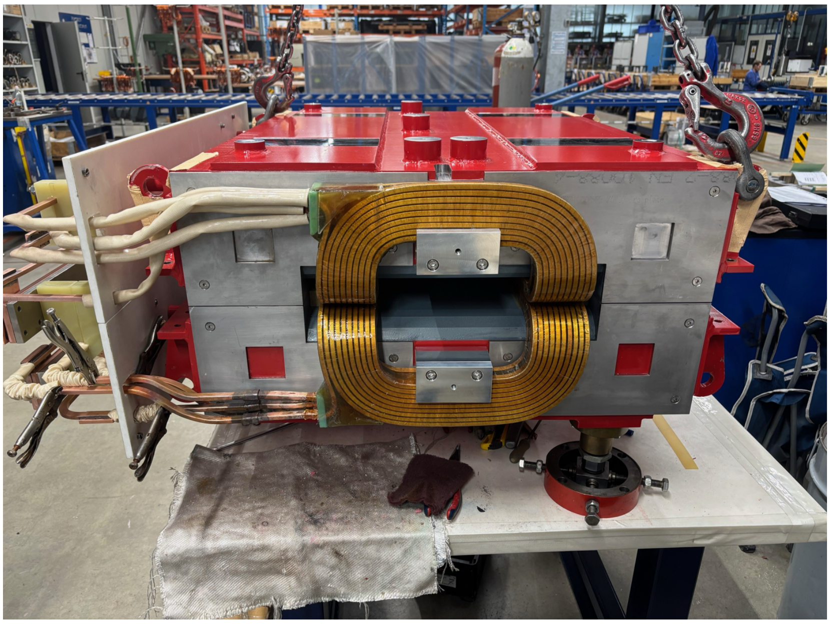


Figure 97: The new M-branch kicker magnet, during assembly at the producer’s

11.3 Accelerator upgrade projects

Progress report on the post-stripper upgrade (PSU) - Alvarez 2.0

Head: Dr. Lars Groening

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 1960ies 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 is ongoing [1].

In 2024, the following goals were achieved:15 of 25 cavity sections with a total of six end plates assigned to the cavities AI, AIIa, and AIIb were delivered. The GSI galvanic workshop was successfully commissioned by Cu-plating a dummy cavity before plating the first cavity section for the series.

Regarding the drift tubes, the study for the longest drift tube of cavity AIV could not be completed because the quadrupole magnet did not meet the requirements of pulsed operation w.r.t. to sufficient fixation. The completion of this study is directly linked to the kick-off for the series production of drift tubes for cavity AI. Since it is the same supplier for both orders, the series production for cavity AI is delayed. The series production of the drift tubes for cavity AIIa at a second supplier is in progress and on schedule for subsequent Cu-plating at CERN's galvanic workshop, where a Cu-plating line for the drift tubes was set up. For the remaining drift tubes of cavities AIIb, AIII, AIV, and their Cu-plating, the planned budget was released by BMBF late in 2024.

In addition, a lot of add-on parts were ordered or procured in 2024. The order of 10 half-drift tubes with internal quadrupole magnets was placed. Seven plates for service access of an outer diameter of 600 mm were Cu-plated externally, the same applies to seven adapter flanges of the same size for RF coupling. As a further example, a total of 400 drift tube heads for applying pre-vacuum and connecting the drift tubes to the cooling circuit were delivered.

Storage areas within GSI's neighborhoods were rented from 2nd half of 2024 on. Regardless of this there are no binding concepts to provide areas on the GSI campus, for pre-assembly and testing of the Alvarez cavities. Areas at the testing hall (TES) were spotted to be the only area, which fits to the requirements of this project.

Highlights

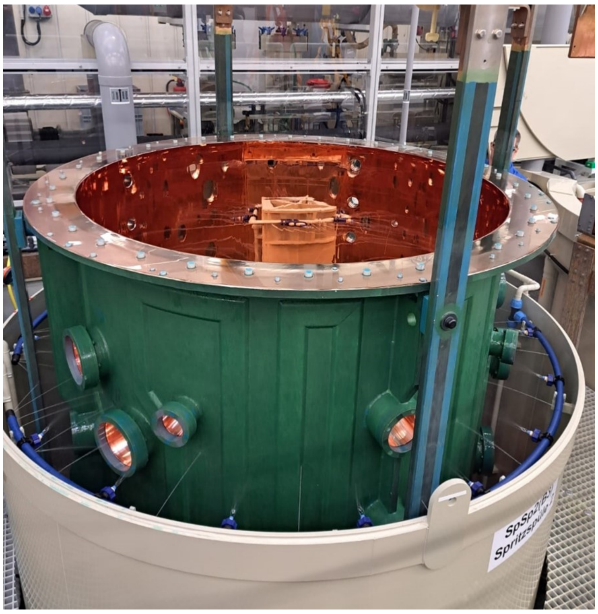


Figure 98: Cavity section AIIa – 5 right after plating at the GSI galvanic workshop (T.Dettinger, GSI).

Figure 99: Quadrupole magnet prototype of the longest drift tube of cavity AIV, which was measured successfully in DC mode (E. Kuipers, Scanditronix)

Figure 100: Cu plating line for the drift tubes during set up @ CERN (L. Ferreira, CERN)

Figure 101: 400 drift tube heads for applying pre-vacuum and connecting the drift tubes to the cooling circuit (Hardcoats India, India)

Figure 102: Unloading of the end plates and cavity sections of cavity AI (S. Mickat, GSI)

Outlook for 2025

In 2025, the remaining 10 cavity sections and four end plates of cavities AIII and AIV shall be delivered. Also, the Cu-plating of the cavity sections at the GSI galvanic workshop shall continue. The decision to provide areas in the testing hall (TES) from 2nd half of 2025 has to be made within the campus development strategy. The areas are needed in the short term for pre-assembly and testing of the Alvarez cavities and in the mid-term for increasing the Cu-plating rate of the large components.

Concerning the drift tubes, the completion of prototyping of the longest drift tube and starting series production of drift tubes for cavity AI is expected. The drift tubes for cavity AIIa shall be delivered to CERN for Cu-plating. The order for the remaining drift tubes of the cavities AIIb, AII, and AIV shall be placed.

The procurement of the power supplies from 2026 to 2029 shall be prepared starting with applying for the release of the budget by BMBF via the GSI supervisory board (*Aufsichtsrat*). The planning of the replacement of the existing Alvarez drift tube linac (DTL) with the Alvarez 2.0 DTL will be an ongoing task. A 3D model of the DTL in the UNILAC tunnel is detailed step by step to plan the necessary shutdown activities for substitution. This involves the ongoing procurement of diverse components for media supply and several add-on parts.

Selected publications of 2024

[1] S. Mickat *et al.*, "Series procurements for the new post-stripper DTL Alvarez 2.0," ch.9.15, p.125ff, *GSI-Scientific Report 2023*, doi: 10.15120/GSI-2024-00500

Pulsed gas-stripper: beam time operation and project status

Head: Dr. Lars Groening (GSI)

Author: M. Maier

High intensity heavy ion beams are a main constituent of the FAIR research program. They will be provided by the UNILAC via the high current injector HSI. Generated in high current sources, these ions originally have low charge states. To allow for efficient acceleration in the UNILAC and SIS18, a gas stripper is located at the end of the HSI to reduce the mass-to-charge ratio below 9.0. An effort has been made to enhance the stripping by introducing hydrogen instead of nitrogen as stripping target, thereby increasing the stripping efficiency by up to 60% [1]. The status of the project is presented in this publication, concluding with an outlook about the next steps towards routine operation of the pulsed hydrogen gas stripper at GSI.

Due to unexpected problems using the jet stripper for the beam time 2024, the pulsed stripper was requested to cover for routine operation during that beam time. This required some fast changes of the until then, experimental setup, to be fit for the beam time. The main adaptation required was to restructure the gas regulation system. It had to allow serving both installed injector valves with two different gasses and individual pressures. To cover all pressure regimes, two low pressure regulators have been installed especially suited for pressures bellow 1.0 bar of absolute pressure. The opportunity to test the pulsed gas stripper in routine operation led to a strong increase of knowledge about the system. To provide efficient stripping, the stripping efficiency for many ion target combinations was measured and documented for future runs as for example shown for uranium beam in Figure 103 and Figure 104.

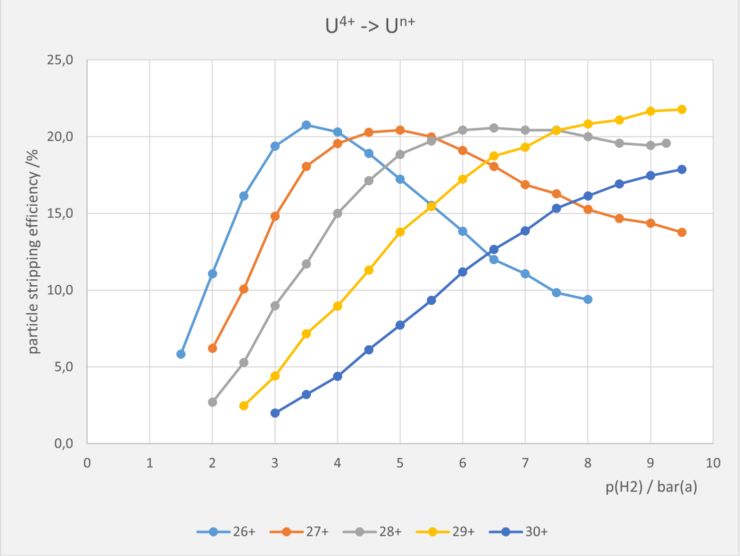


Figure 103: Stripping efficiencies of uranium beam in hydrogen gas as a function of the gas pressure.

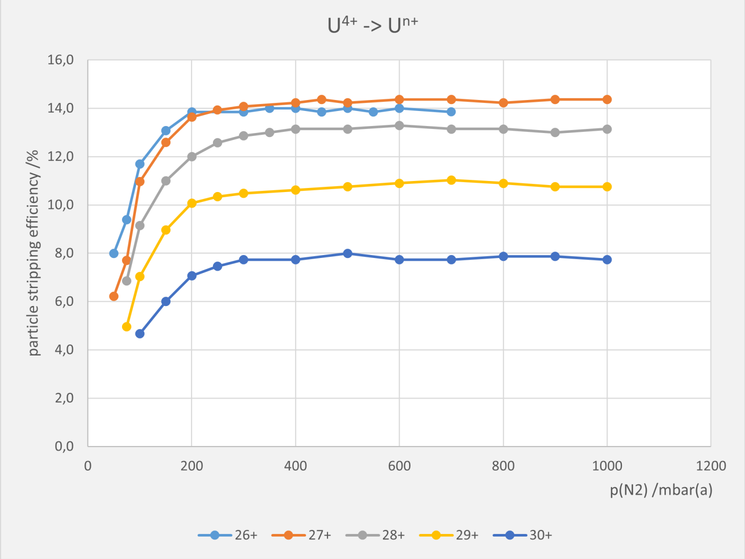


Figure 104: Stripping efficiencies of uranium beam in nitrogen gas as a function of the gas pressure.

On the other hand, there were also many lessons learnt about the deficits of the system. During the beam time, a more than expected consumption of oil of the floating ring seal has been observed. Several operational parameters of the roots pump have been tested in order to determine their impact on the consumption and an oil dump has been installed to drain the excessive floating ring seal oil from the pump bearing. The later allowed to double the continuous operation of the roots pump to about 30 days. Yet, the excessive oil leakage of the floating ring seal still persisted.

Besides full beam time coverage in 2025 using the pulsed stripper setup, it is necessary to proceed towards routine operation within the GSI control system allowing for full hydrogen coverage of the beam time. To achieve this, electronic pressure controllers have been ordered and successfully tested and will be routinely used in the upcoming beam time 2025. The simulations of a vacuum exhaust mixing chamber, to render the hydrogen inert and safely channel it through the regular GSI vacuum exhaust line, is in progress and it is expected to have a practical solution by autumn 2025. The stripper setup itself will get an upgrade from the actual V-shape stripper, hosting two valves, to a X-Shape configuration hosting four valves. This will increase the flexibility as well as the service lifetime of the pulsed gas stripper.

References

[1] P. Gerhard *et al.*, “Development of Pulsed Gas Strippers for Intense Beams of Heavy and Intermediate Mass Ions,” in *Proc. LINAC’18*, Beijing, China, Sep. 2018, pp. 982–987, doi: 10.18429/JACoW-LINAC2018-FR1A05

Status of the UNILAC control system upgrade

Head: Dr. Lars Groening

Author: P. Gerhard

The UNILAC control system upgrade started end of 2019 as the first and major part of a broader Injector Controls Upgrade (ICU) project. 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. For the UNILAC, this means replacing the current legacy control system, which dates back to the 1990s and is becoming increasingly outdated and unmaintainable. The front-end layer, which controls the actual accelerator equipment, will not be replaced within the scope of the project. Due to the pending move of the Main Control Room (MCR) to the new FCC building and its associated complete digitization, this project includes the replacement of more than 100 analogue and hardware-based systems and equipment located in today's MCR, which will not be relocated to the FCC.

In 2023, the actual replacement strategy for the UNILAC control system was decided on, taking into account the commitment to ensure proper support of all scheduled user beamtimes:

- operation up until and including the user beamtime 2025 will be based on the legacy control system, which received a service life extension and will be maintained including the integrated timing system (Pulszentrale).
- the development path contains an intermediate, minimum viable version of the new control system available since end of 2024. This version allows for limited standalone operation and serves for evaluating the technical basis as well as mitigating the risk of the legacy control system failing during the 2025 beamtime, therefore being named "emergency control system".
- after the user beamtime 2025, operation of UNILAC will solely be based on the new control and timing system. This is represented by stepping up from the intermediate "emergency" to the "production control system," the initial version of which will be available for the user beamtime 2026.

The year 2024 saw two major development milestones of the new control system:

- in July, a dedicated 3-week dry run provided the first comprehensive test of the intermediate control system, following a first successful limited scale test including parts of the settings generation and data supply already in November 2023. Standalone operation with the new control and timing system was achieved successfully. Thereby, completeness of the core functionality could be demonstrated using realistic test scenarios, also verifying the main capabilities of the emergency control system.
- in October, another dry run was conducted, followed by a 1-week wet run in November. For the first time, an ion beam was accelerated from the high current injector through the main linac and the transfer channel leading to the SIS18 with UNILAC operated via the new control system. Injection into the synchrotron could only be simulated due to the ongoing shutdown and hence unavailability of the SIS18. Parallel operation of two beams serving multiple users was demonstrated successfully. As anticipated, the test also confirmed that the current development state still lacks in operational efficiency, leading to dependencies on the legacy system and MCR equipment still present in order to achieve the test run goals in the time available. This will be improved during the next project stage.

In order to accomplish these achievements, a lot of fundamental developments and conceptual work had to be done across the ACO department and beyond. UNILAC operation requires data supply and timing changes to be performed while the accelerator runs continuously delivering 50 beam pulses per second, which represents a new paradigm contrasting requirements of the rest of the GSI facility. Correspondingly, UNILAC specific timing event generation has been implemented in LSA. The distribution of these events is handled via a separate UNILAC Data Master accompanied by 7 additional White Rabbit-to-MIL gateways providing timing to the legacy Device Access type frontends. A new kind of beam scheduling had to be conceived, employing multiple timing graphs and processing threads in the Data Master, containing and broadcasting the super cycle (sequence of individual beams for users) and the individual accelerator event sequences. Setup and generation of the pre-computed super cycle and other UNILAC specific functions have been implemented in a dedicated application, while other, already existing applications had to be adapted. A specialized feature for handling UNILAC sections incapable of multiplexing set values, previously unused at GSI, has been adapted from CERN's code base. The accelerator model, responsible for the settings generation for over 1000 devices, has been completed using a fully scripted generation of the code based on the database representation of the facility, thereby facilitating future improvements and developments. Currently, in order to make the model available in time for the intermediate control system, some aspects were simplified and compromises had to be made regarding operation efficiency, to be improved until the beamtime 2026. A new real-time chopper control interface has been implemented in support of the replacement of the timing and interlock system components of the Pulszentrale, while the chopper control system itself will be preserved.

Basic operational capability of the new control system has been demonstrated during the wet run. Further development and improvement are necessary in order to reach an adequate level of operational efficiency and reliability for the user beamtime 2026, taking the step from the intermediate "emergency" to the "production" control system. The next major milestone is a 3-week wet run after the 2025 user beamtime, when beam will be injected into SIS18 using the FAIR style control system for both accelerators for the first time.

HEST - Upgrades

Head: Dr. Stephan Reimann (GSI)

Author: C. Hessler

The High-Energy Beam Transfer lines at GSI (HEST) serve the experimental caves downstream SIS18 as well as the storage rings ESR and CRYRING@ESR with beam. Furthermore, a small part of HEST will be used to transport the beam to the FAIR high-energy beam transfer lines (FAIR-HEBT), which then will transport the beam to SIS100 and the Super-FRS. Several upgrade measures for the HEST beamlines are ongoing or have been completed in 2024, which will be discussed in this article.

Upgrade of luminescent screen stations

Part of the luminescent screens installed in HEST are still equipped with analog cameras. These cameras must be replaced with digital cameras because the control room will be relocated to the new FAIR Control Center (FCC) in 2026. The new control room will be fully digital without analog cable links. Furthermore, analog cameras are disappearing from the market and the spare situation is becoming more and more difficult. Therefore, an upgrade project of the luminescent screen stations in HEST was started in 2023 [1] to replace the remaining analog cameras with digital ones and to integrate them into the CUPID system (Control Unit for Profile and Image Data). The upgrade also includes an adaptation of the mechanics (pneumatic drives) and a modification of the corresponding diagnostic vacuum chambers to equip them with fiducials for precise adjustment of the screen position.

In 2024, the upgrade of the screen stations in the beamline towards HADES has been completed: Two regular screen stations have been upgraded as well as the camera, which observes the pion target via a mirror and which is placed in several meters distance outside the pion bunker. It was important to complete the CUPID upgrade in the HADES beamline before the upcoming HADES pion run, which was originally foreseen for the beamtime 2025, because the resulting activation level might not allow work close to the HADES beamline immediately after the pion run.

The six remaining analog cameras have to be upgraded during shutdown 2025. The cables for these cameras have been already installed in 2024.

Maintenance and upgrade of stripper in TE beamline

Major maintenance and upgrade works have been performed for the stripper in the beamline towards the ESR (TE beamline). This stripper is equipped with several copper and carbon foils of different thicknesses for changing the charge state of the ion beam, but also with a beryllium target used for isotope production. Work on the stripper was required because an experiment required an additional aluminum target for isotope production, and one of the installed copper foils has been damaged during beamtime 2023.

The task was challenging because the last target exchange in the stripper was in 2003 and the experience on this device got lost over the years due to the lack of documentation and the fact that nobody who was involved in the last target exchange is still working at GSI today. Furthermore, no technical group is responsible for this stripper and as of beginning 2024 no technical drawings of the stripper were known. In addition, the installed beryllium target required special safety precautions.

In a first step, the new aluminum target for isotope production has been installed on a new separate pneumatic drive just in front of the existing stripper assembly during the maintenance break around Eastern 2024 (Figure 105). This target has successfully been used during the remaining beamtime 2024 afterwards.

After retrieving the technical paper drawings of the stripper and gaining the understanding of the mechanism, all stripping foils have been exchanged with newly produced foils in a second step during summer 2024. A spare target holder has been produced and documentation has been created.

In a final step, additional concrete shielding has been installed downstream the stripper adjacent to the TE beamline to reduce the radiation level inside the nearby HHT cave generated during isotope production at the stripper.

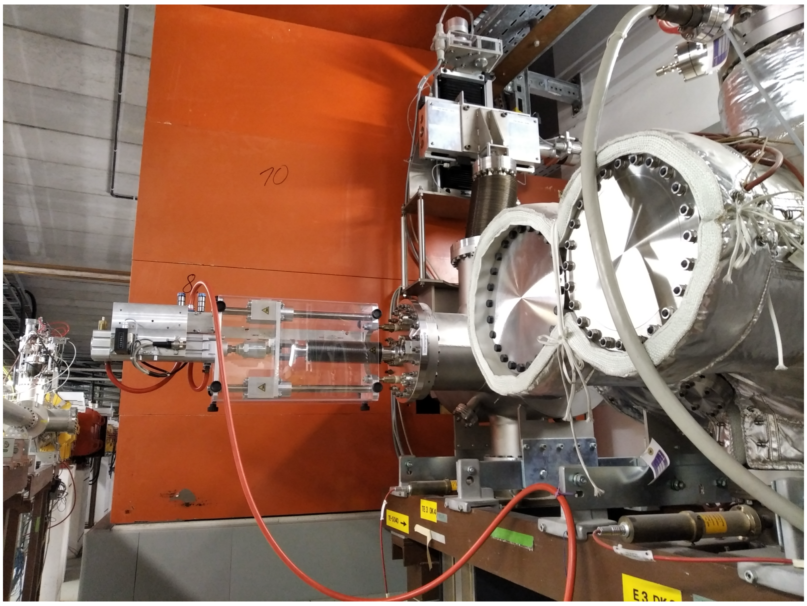


Figure 105: View onto the stripper assembly in the TE beamline. The new pneumatic target drive holding the aluminum target is mounted horizontally on the left flange in front of the old stepping motor target drive, which is mounted vertically on the top flange.

Upgrade of vacuum system

The vacuum system of the HEST beamlines consists of a large number of ion getter pumps. These pumps are more than 30 years old and are aging. Therefore, all required replacement pumps have been purchased over the last years and the exchange of the pumps has started. In order to perform the work in a resource-efficient way, pumps are replaced whenever a vacuum sector is vented for other reasons. So, ion getter pumps were exchanged in the shadow of the CUPID and stripper upgrades during the 2024 shutdown, and the work will continue in upcoming shutdowns.

HEST virtual tour

A virtual tour through the different HEST areas has been created (Figure 106). It allows moving, turning and zooming, similar to the well-known Google Street View. For this virtual tour, numerous high-resolution 3D panorama images have been taken and processed using the software Pano2VR. The aim of this virtual tour is to have a possibility to inspect beamline details when access to HEST is not possible during beam operation. The virtual tour has already been extended to UNILAC and SIS18.

Figure 106: Example view in the HEST virtual tour.

Selected publications of 2024

[1] Hessler, C.; Boutachkov, P.; Geithner, O.; Reiter, A.; Walasek-Höhne, B., “HEST Beam Diagnostics Upgrade,” *GSI Scientific Report 2023*, doi: 10.15120/GSI-2024-00500

11.4 Accelerator R&D Activities

Production of Manganese ion beams with the ECR Ion Source

Head: Dr. Fabio Maimone (GSI)

Author: F. Maimone, A. Andreev, M. Galonska, R. Hollinger, R. Lang, J. Mäder

The CAPRICE Electron Cyclotron Resonance Ion Source (ECRIS) at the High Charge State Injector (HLI) of GSI is routinely used for the production of highly charged ion beams from both gaseous and metallic elements. The latter are produced utilizing the thermal evaporation technique by resistively heated ovens. A high demand of metal ions comes from the nuclear physics, material research, and Super Heavy Element group (SHE). A recently requested element was Manganese. To meet their demand, a test campaign was conducted at the EIS testbench to establish and improve the production of ^{55}Mn ion beam, i.e. to determine the achievable ion beam intensity of higher charge states with a focus on $^{55}\mathrm{Mn}^{9+}$. Additionally, the use of a hot screen was investigated to protect the ceramic insulators in the extraction system from metal deposition, thereby improving the operational stability of the ECRIS. [1].

An average intensity of 80 μA has been achieved for $^{55}\mathrm{Mn}^{9+}$. Discharges appeared in the extraction system on the second day of ECRIS operation. However, their frequency was low enough to maintain stable operation. It has been confirmed that the use of the hot screen improved beam stability and delayed the onset of discharges, enabling stable operation at high intensities with minimal disruptions. as shown in Figure 107. Without using the hot screen discharges every few minutes started occurring after one day of operation (Figure 107 right) while the hot screen delayed their appearance to the second day of operation and reduced their frequency (Figure 107 left).

A typical mass-to-charge spectrum for ^{55}Mn obtained during the tests is shown in Figure 108. An overall average consumption of ^{55}Mn material of 8.1 mg/h (without material recycling) has been measured. The installation of a tungsten mesh to shield the oven orifice from the coupled microwaves, as performed for Calcium ion beam production, has been investigated and experiments with the shielding mesh have been also carried out. However, for ^{55}Mn operation the mesh was completely clogged with condensed material after one day of the ECRIS operation, preventing further Manganese evaporation and beam production. Further long run tests are planned by using a real-time diagnostic system based on an CCD camera and an optical emission spectrometer to guarantee routine and stable operation.

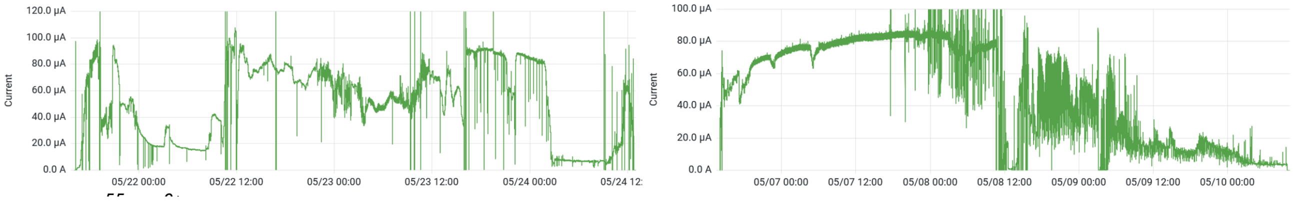


Figure 107: $^{55}\mathrm{Mn}^{9+}$ intensity at the Faraday Cup with hot screen (left) and w/o (right).

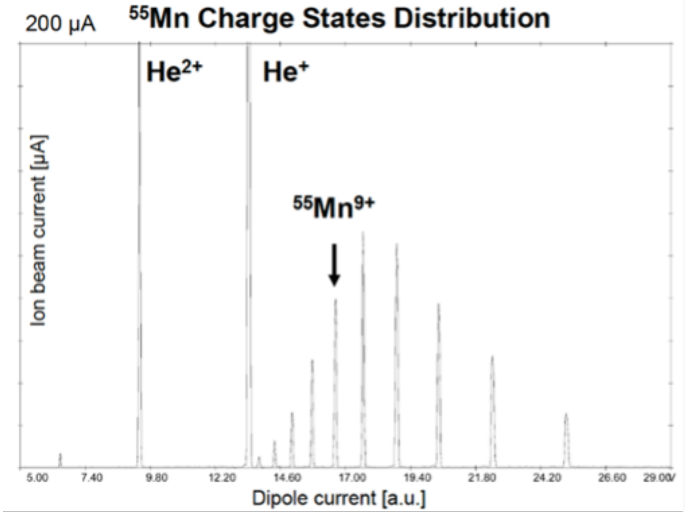


Figure 108: Optimized charge states distribution of ^{55}Mn.

Selected publications of 2024

[1] A. Andreev *et al*, to be published in *Proc. of the ECRIS24* - 26th Workshop on ECRIS, 15.-19.09.24, Darmstadt, Germany, doi: 10.18429/JACoW-ECRIS2024

Operation of the PIG ion sources with main highlight in production of $^{52}Cr^{2+}$ and development of $^{55}Mn^{3+}$

Head: Dr. Ralph Hollinger (GSI)

Author: 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 109 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 110. 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).

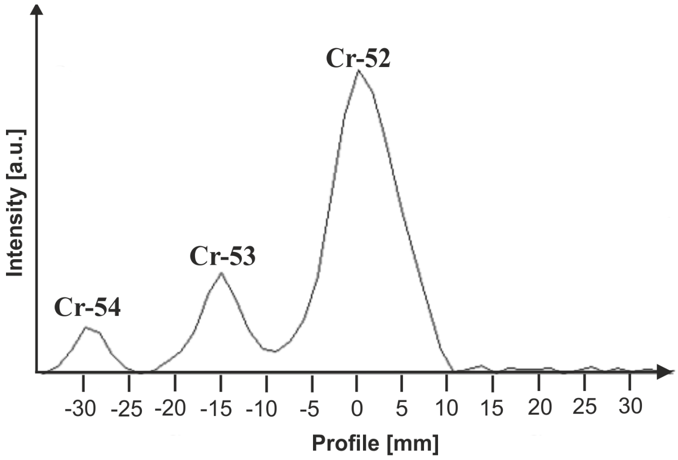


Figure 109: 52-Cr, 53-Cr and 54-Cr at profile grid GUR5DG7.

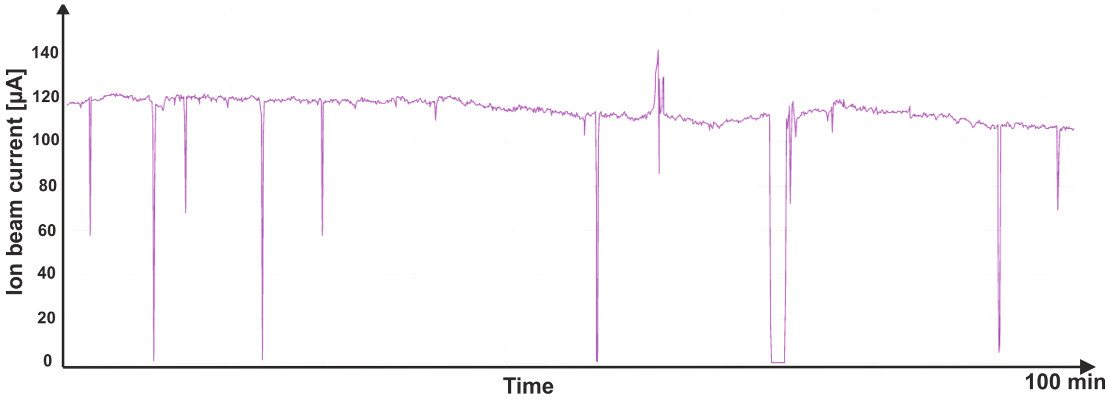


Figure 110: Operation stability and intensity of $^{52}Cr^{2+}$ over 100 min at beam transformator GUR5DT8.

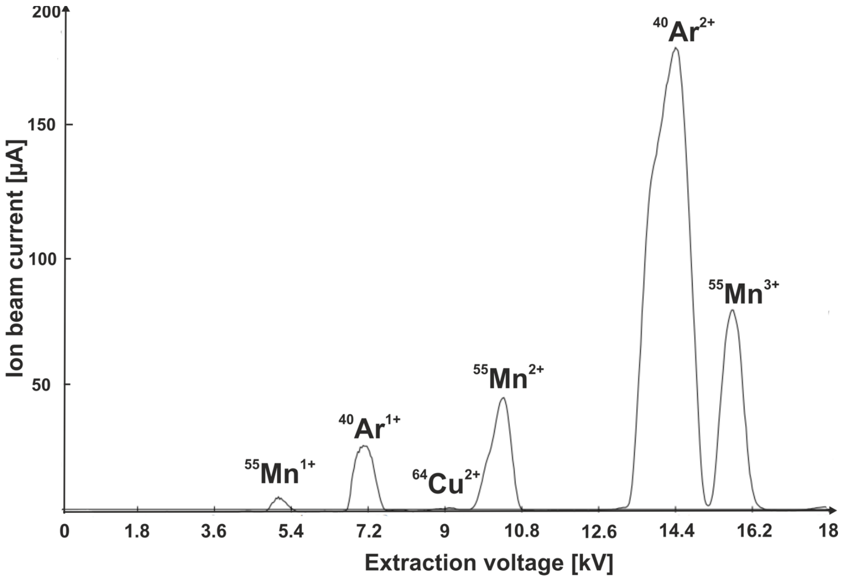


Figure 111: IMG3: Manganese, argon and copper charge spectrum.

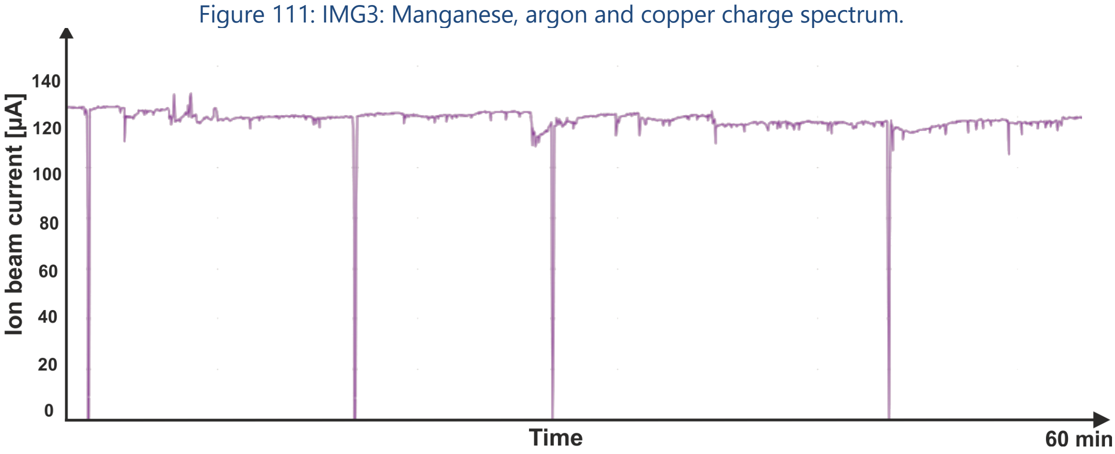


Figure 112: IMG4: Operation stability and beam intensity of $^{55}Mn^{3+}$ over 60 min measured in section GUR5DT8.

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 111 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 112. 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.

HELIAC CM1 commissioning

Head: Uwe Scheeler (GSI)

Authors: M. Miski-Oglu, W. Barth, F. Dziuba, V. Gettmann, J. List, T. Kuerzeder, U. Scheeler, H. Vormann, S. Yaramyshev

The Advanced Demonstrator, which serves as a prototype cryogenic module (CM) for the future continuous wave (cw) linac HELIAC (HElmholtz LInear ACcelerator) at GSI, has been installed in a radiation protection shelter inside of a test area since mid-2023. Two successful campaigns with ion beams have already been completed, one in December 2023 with He^{2+} beam and the other in June 2024 with $^{40}Ar^{8+}$ beam. Figure 113 shows the layout of cryogenic CM1. It is equipped with three superconducting (SC) Crossbar H-mode (CH) cavities CH0-CH2 with maximum design accelerating gradients up to E~a, design~ = 7 MV/m, a SC buncher (B) cavity with E~a, design~ = 5 MV/m, as well as two 9 T SC solenoids (S1, S2).

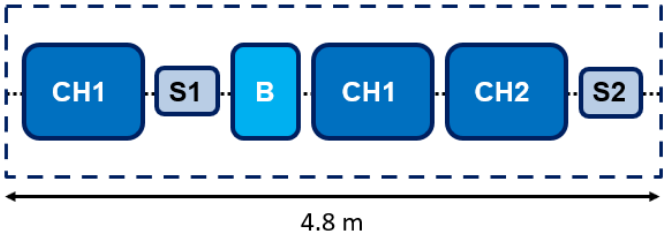


Figure 113: Layout of the Advanced Demonstrator cryogenic module. It contains sc CH-cavities CH0-CH2, RF-buncher B, and SC solenoids S1 and S2.

The test area is connected to the cryogenic plant of the GSI series test facility (STF). The cryogenic distribution system at the test area is in operation since 2020. In preparation for beam testing activities, the beamline connecting the High Charge State Injector (HLI) to the test area was installed and beam-tested in 2021. The matching beamline consists of a pair of phase probes for time-of-flight (TOF) measurement of the incoming beam energy, quadrupole lenses for transverse matching and a 4-gap RF-buncher cavity for longitudinal matching. The beam diagnostics bench behind the cryostat is equipped with a pair of phase probes to measure the output beam energy, a slit grid to measure the transverse beam emittance and a Feshenko Bunch Structure Monitor (BSM) to measure the longitudinal beam profile. This setup allows for complete 6d characterization of the ion beam. All beam instrumentation was commissioned with beam prior to cooling down of the cryomodule.

The typical cool down procedure is as follows: the local helium distribution system and the radiation shielding of the cryostat were cooled in less than two days and were ready for cooling of CM1. After cooling of the radiation shield, the temperature of the RF-cavities was 220 K. In the temperature range from 150 K to 50 K, niobium hydride (NbH_5) can form on the RF-surface of the cavities and lead to so-called Q-disease, a dramatic degradation of the quality factor. To avoid the formation of NbH_5 on the RF-surface of the superconducting cavities, they should be cooled at a cooling rate of 1 K/min. The liquid helium from the DB01 distribution box was injected into the 4 K system of the cryomodule. Since November 2023, a total of six cold campaigns were completed. The average cooling rate of 0.6 K/min in each cold run was slower than intended, but fast enough such that no Q-decease was observed. The main limitation is due to the maximum design absolute pressure for RF-cavities of 1.5 bar and the inlet pressure at the quench buffer of the STF. After a cooling period of approximately 12 hours, the RF-cavities are completely immersed in liquid helium. RF-conditioning of the four cavities was performed sequentially using two vector network analyzers (VNA). The forward RF-power provided by the 3 kW RF-amplifiers was gradually increased until the multipacting barriers disappeared. For further conditioning and measurement of the acceleration gradient, the cavities were operated in phase-locked loop (PLL) mode. In this mode, the RF-generator tracks the resonant frequency of the superconducting cavity, which varies strongly with pressure in the 4 K He-system of the cryostat. The pressure fluctuation of 1 mbar in the He-system leads to a change of the resonance frequency of about one band-width of the cavity. In May 2024, a dedicated cold campaign for the measurement of the unloaded quality factor Q_0 was completed. The RF-power coupler penetration depth was reduced to achieve the appropriate coupling strength b=10 for reliable RF-power accounting.

Figure 114 shows the measured unloaded quality factor as a function of accelerating gradient for all three cavities.

The design acceleration gradient of cavity CH0 is 5.5 MV/m, and it reached a maximum of 6 MV/m during RF-conditioning being limited by thermal quenching. The design gradient for cavities CH1 and CH2 is 6. MV/m, respectively. They reached maximum gradients of 11 MV/m and 10.5 MV/m, respectively, being well above the design. These cavities are equipped with a µ-metal shield against the earth's magnetic field. Due to lack of time and budget, CH0 was not equipped with a metal shield, which is probably the reason for the relatively low maximum gradients.

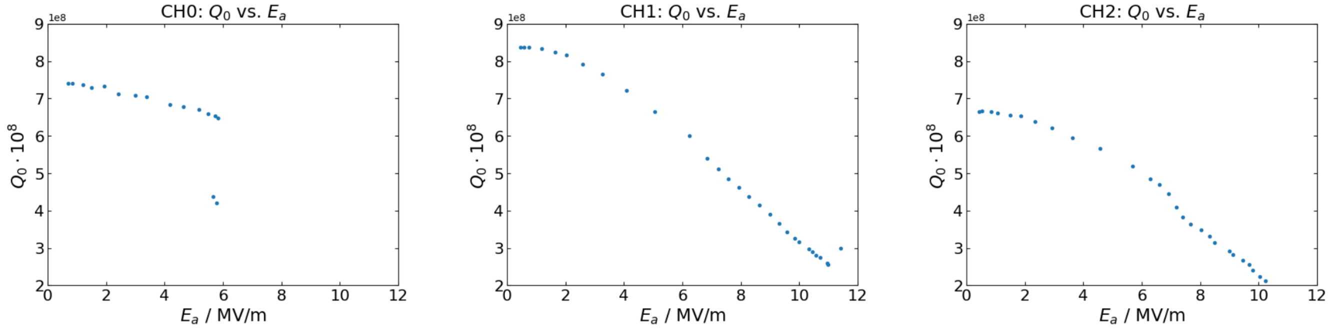


Figure 114: Measured unloaded quality factor Q_0 as a function of the accelerating electric field E_a for superconducting cavities CH0, CH1, and CH2 within first cryogenic module CM1.

A generator-driven system with constant master RF-frequency was used for operation of the cavities with beam. In this mode, the resonant frequency of the cavity is kept constant by a piston tuner driven by a piezo actuator. The amplitude and phase of the cavities are controlled by the same analogue low-level RF-system as the normal conducting cavities of the existing UNILAC. In this mode, pondermotive instabilities of the feedback system occurred. The detuning of the resonant frequency of CH1 and CH2 due to ponderomotive forces at the design gradient is 1.5 kHz, which is significantly larger than the 25 Hz bandwidth of the cavities. In December 2023, stable operation of cavities CH1and CH2 was possible just with a gradient of up to 2 MV/m. For the beam test in June 2024, the coupling strength was increased by moving the RF-power coupler deeper into the cavity. This lead to a bandwidth of 120 Hz with stable operation of the feedback system. Cavities CH1 and CH2 achieved gradients of up to 5 MV/m each. These gradients allow acceleration of $^{40}Ar^{8+}$ ions, i.e., A/q=5, up to the design output kinetic energy of the cryogenic module of 2.7 MeV/u.

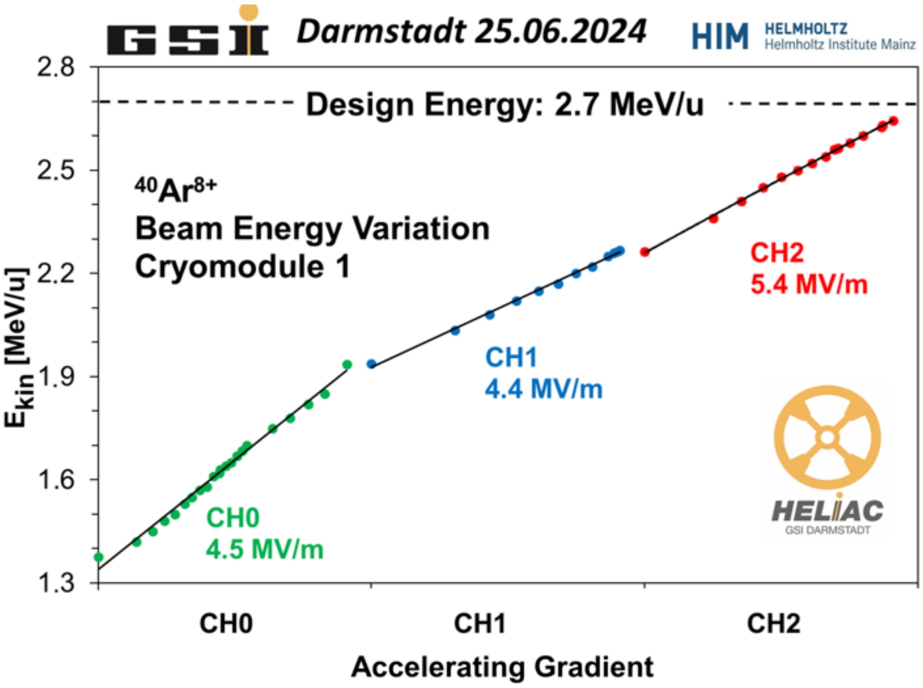


Figure 115: Measured kinetic energy of accelerated $^{40}Ar^{8+}$ ion beam.

Figure 115 shows the TOF-measured kinetic energy of the argon beam as a function of the accelerating gradient of the cavities. During beam commissioning, the cavities were powered up sequentially. First, the acceleration gradient of CH0 was ramped up and the phase of the RF-field was tuned to provide for maximum kinetic energy. The CH1 and CH2 cavities were then ramped up using the same recipe. Finally, the design kinetic energy was achieved. The significant improvement in stability could be achieved with a dedicated low-level RF (LLRF) feedback system based on self-exited loop principles. This type of LLRF is well proven in the operation of superconducting LINACs around the world, e.g., FRIB, CEBAF, and TRIUMPF. The development of such a system based on FPGA is of great importance. A prototype based on the Red Pitaya board is currently under development at the LINAC department. The analysis of the longitudinal bunch profiles measured with BSMs indicates that the longitudinal matching of the HLI injector and CM1 is not ideal. Its improvement will be the subject of further beam campaigns.

3D-Printing for Particle Accelerators and Storage Rings

Head: Dr. Chuan Zhang (GSI)

Authors: Chuan Zhang, Roland Böhm, Eduard Boos, Ramy Cherif, Alexander Japs, Stefan Wunderlich

The state-of-the-art 3D-Printing technology provides not only a new manufacturing method but also more design freedom for particle accelerators and storage rings. The RACE (Resonators Additively Constructed for Experiments) team led by the Stochastic Cooling Group (SCO), GSI, is worldwide one of the first teams working on this topic. Some technical progresses of the ongoing projects will be presented.

Metal 3D-Printing for Linear Accelerators

The proposal and the first design of a novel 704.4 MHz CH (Cross-bar H-mode) cavity was published in 2021 [1]. 704.4 MHz is almost twice the highest frequency of all so-far-built H-mode structures i.e., 360 MHz and the spatial dimensions of this table-top cavity (22 cm in diameter and 33.7 cm in length) are so small that it has been foreseen to be realized using the modern 3D-printing technology [1]. Some early R&D on the cavity design and a 3D-printed copper model can be found in [1][2][3][4]. One highlight is the novel cooling-channel design of the electrode enabled by 3D-printing, which uses 8 slimmer channels (Ø = 3 mm, see Figure 116) instead of one thick channel for cooling the stems and these 8 channels will be merged as 4 channels in the drift-tube part so that the maximum surface temperature of the electrode can be reduced by >30 °C at a thermal load of 600 W [3][4].

Figure 116: (a) Mechanical design of the 704.4 MHz table-top CH; (b) a copper-printed electrode after post-processing (left) and CT scan of a printed electrode before post-processing (right); (a) the 704.4 MHz cavity presented at GSI ACC Performance Committee Meeting on July 18th, 2024.

In 2024, the 704.4 MHz CH was completely printed with the electrodes in pure copper and the tank in stainless steel, respectively. The first low-level RF test of the 704.4 MHz cavity has been done in February 2025 at IAP Frankfurt. The design frequency was reached and the measured *Q*-value and gap-voltage distribution are comparable to the CST simulation results. As next steps, vacuum tests, a second low-level RF test after the copper-plating, and high-power RF measurements will follow.

Metal 3D-Printing for Storage Rings

A 1–2 GHz stochastic cooling system is being developed at GSI for the Collector Ring of the FAIR project to provide fast 3D cooling of hot secondary beams (antiprotons at 3 GeV and rare isotope ions at 740 MeV/u) at intensities up to 10^8 particles per cycle, where the kicker part has been designed by Forschungszentrum Jülich [5]. Each of the two kickers contains 128 slot-rings and every 16 slot-rings are grouped into 1 stack and attached to 8 divider boards (see Figure 117). The boards must not only withstand high RF power but are also frequently placed in vacuum environments with suboptimal cooling conditions, posing a risk of catastrophic resistor failure. Careful simulations were also performed for the worst case (a sudden power increase to 95 W on the board) and showed that the temperature of the resistors could rise to ~110 °C within a short time of 0.1 s (see Figure 117).

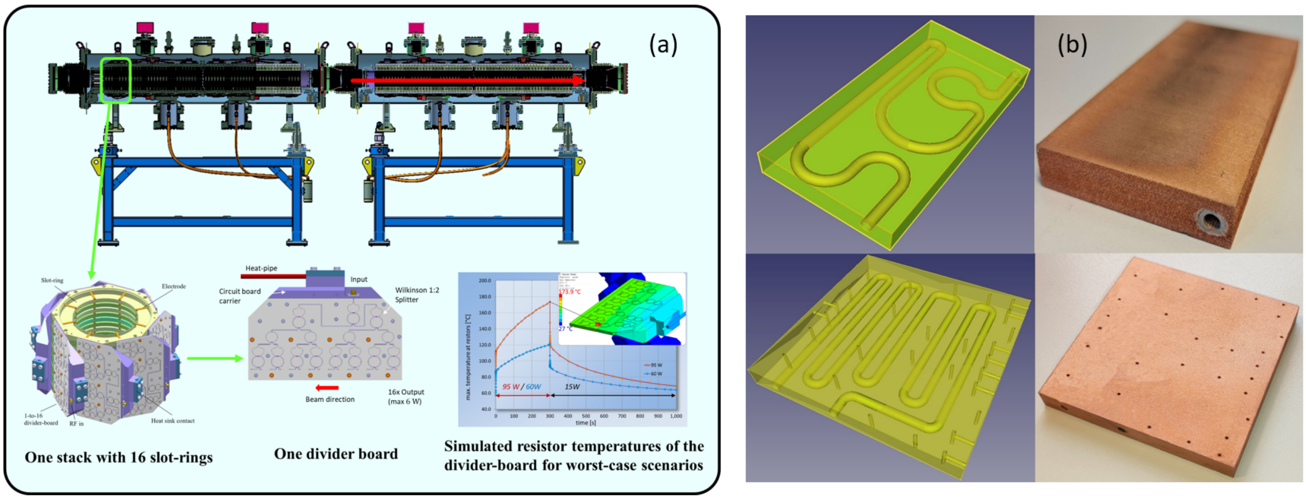


Figure 117: (a) Kickers for the FAIR Collector-Ring Stochastic-Cooling System [5]; (b) 3D-printed copper board-prototypes (top: with a “SCO”-logo cooling-channel inside, bottom: with another cooling-channel design).

A water-cooling system inside the divider board can help increasing its power handling capabilities greatly, but typically only a heat sinker is attached to the board side for the cooling, because it is impossible to realize cooling channels inside such a thin board using the traditional manufacturing methods. Proposed by the GSI-RACE Team, two new-style divide-board prototypes (dimensions: 48.5 mm x 97.0 mm x 10.0 mm and 97.0 mm x 97.0 mm x 10.0 mm, respectively) with internal cooling channels (both diameters: 4.0 mm) have been produced taking advantage of the metal 3D-printing technology. For the prototype with a “SCO”-logo cooling channel inside, stainless steel and copper have been used for printing the cooling channel and the board body, respectively. The reason for this design was that stainless steel could provide a much longer life time against the water damage. Another prototype printed with pure copper will be used for comparison studies. As next steps an extensive qualification campaign regarding vacuum quality, thermal conductivity, water-tightness etc. of the printed prototypes will be performed.

Acknowledgement

Special thanks go to the GSI Workshop (especially M. Romig, S. Teich, R. Erlenbach and M. Uhlig) and The GSI Technology Lab for the post-processing and analyses as well as to the IAP Frankfurt colleagues (especially H. Podlech, J. Storch and D. Bänsch) for the help in low-level RF measurements.

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12. Annex

12.1 GSI and FAIR committees in the year 2024

Compiled by T. Beier & K.Füssel

Director’s Board / Geschäftsführung

- Scientific Managing Director: Prof. Dr. Paolo Giubellino (until 06/2024), ad interim head: Dr. Yvonne Leifels, Prof. Dr. Thomas Nilsson (since 12/2024)
- Administrative Managing Director: ad interim head: Markus Jaeger, Katharina Stummeyer (since 06/2024)
- Technical Managing Director: Jörg Blaurock

Shareholder Assembly / Gesellschafterversammlung, GSI

- Philipp Strauchmann [chair], Bundesministerium für Bildung und Forschung (Germany), as chair, and representative of the Federal Republic of Germany
- Stephanie Schinzel, 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 Bildung und Forschung, Bonn/Berlin (Germany)
- Ralph Dieter, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany)
- Ulrike Mattig [vice chair], Hessisches Ministerium für Wissenschaft und Kunst, Wiesbaden (Germany), until 12/2023;
- Christine Burtscheidt [vice chair], Hessisches Ministerium für Wissenschaft und Kunst, Wiesbaden (Germany) since 01/2024
- Jana Podßuweit, Thüringer Ministerium für Wirtschaft, Wissenschaft und Digitale Gesellschaft, Erfurt (Germany)
- Miriam Hirsch, Ministerium für Wissenschaft und Gesundheit Rheinland-Pfalz, Mainz (Germany), until 01/2024
- Simone von Stockhausen, Ministerium für Wissenschaft und Gesundheit des Landes Rheinland-Pfalz, Mainz, (Germany) since 02/2024 up to 12/2024
- Thomas Nilsson, Chalmers University of Technology, Göteborg (Sweden), as Vice-Chair of the Joint Scientific Council GSI/FAIR until 10/2024
- Marialuisa Aliotta, University Edinburgh (UK), as Vice-Chair of the Joint Scientific Council GSI/FAIR since 10/2024
- Thomas Glasmacher, Facility for Rare Isotope Beams, East Lansing (USA)
- Cornelia Denz, Westfälische Wilhelms-Universität Münster (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 Bildung und Forschung, Bonn/Berlin (Germany)
- Dirk Steinbach, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany), as representative of the Federal Republic of Germany
- Christine Burtscheid, Hessisches Ministerium für Wissenschaft und Kunst (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 representative of the Swedish/Finnish Consortium
- Sofie Björling, Swedish Research Council (Vetenskapsrådet),
  as representative 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

Advisors and Guests of the FAIR Council

Maximilian Jedemann, Bundesministerium für Bildung und Forschung (BMBF); Christine Klingbeil, Bundesministerium für Bildung und Forschung (BMBF); Philipp Strauchmann, Bundesministerium für Bildung und Forschung (BMBF); Marco Grumler, Econum Unternehmensberatung GmbH; Peter Bogdanov, Rosatom Nuclear Energy State Corporation; Oleg Patarakin, Rosatom Nuclear Energy State Corporation; Victor Varentsov, FAIR; Mikhail Rychev, NRC Kurchatov Institute; Sanjeev Kumar Varshney, Department of Science and Technology; Sanjay Kumar Ghosh, Bose Institute; Rajarshi Ray, Bose Institute; Ramanuj Banerjee, Counsellor (Sc. & Tech); Supirya Das, Bose Institute, Gaurav Aggarwal, Department of Science and Technology; Maciej Chorowski, Wrocław University of Science and Technology; Dariusz Bocian, Institute for Nuclear Physics of the Polish Academy of Science, Thomas Nilsson, Chalmers University of Technology; Antti Väihkönen, Helsinki Institute of Physics; Ionel Andrei, Extreme Light Infrastructure - NP (ELI-NP); Catalin Borcea, Horia Hulubei National Institute of Physics and Nuclear Engineering; Paul Indelicato, Sorbonne Université Campus Pierre et Marie Curie; Alicja Nowakowska, Jagellonian University Krakow; Örjan Skeppstedt, Stockholm University; Alex C. Mueller, ACM Consult GmbH; Wolfram Fischer, Brookhaven National Laboratory; Hakan Danared, European Spallation Source ERIC; Jens Dilling, TRIUMF; Christofas Touramanis, University of Liverpool; Zsolt Podolyak, University of Surrey.

Scientific Secretary: Thomas Beier.
Deputy Scientific Secretary: Inti Lehmann.

Administrative and Finance Committee (AFC), FAIR

A. Nowakowska, Jagellonian Univ. Krakow, Poland [chair];
A. Väihkönen, Helsinki Institute of Physics, Finland [vice chair];
Cekic, CNRS, France; P. Sassier, CEA, France; M. Jedemann, BMBF, Germany; O. Lindemann, HMWK, Germany; Chr. Klingbeil, BMBF, Germany; M. Grumler, ECONUM Consulting GmbH, Germany; Ph. Strauchmann, BMBF, Germany; V. Sahay, Dep. Science and Technology, Government of India; G. Aggarwal, Dep. Science and Technology, Government of India; S. Kumar Ghosh, Bose Institute, India; R. Banerjee, Counsellor (Sc. & Tech); G. Nowicka, Jagiellonian University Krakow, Poland; , P. Salabura, Jagiellonian University Krakow, Poland; C. A. Ghinescu, Ministry of Research, Innovation and Digitization, Romania; G. Teodorescu, Ministry of Research, Innovation and Digitization, Romania; P.V. Bogdanov, Rosatom Nuclear Energy State Corporation, Russia; V. I. Savosin, Rosatom Nuclear Energy State Corporation, Russia; V. L. Varentsov, FAIR; M. Rychev, XFEL; A. Kralj, Ministry of Education, Science and Sports, Slovenia; D. Palmqvist, Swedish Research Council, Sweden; M. Särkioja, Suomen Akatemia, Finland; T. Gray, United Kingdom Research and Innovation - Science and Technical Facilities Council (UKRI-STFC), United Kingdom.

Scientific Secretary: Thomas Beier.

Joint Scientific Council of GSI and FAIR (JSC)

P. Indelicato [chair FAIR Scientific Council], Lab. Kastler Brossel, CNRS, Paris (France);
Th. Nilsson [vice-chair FAIR Scientific Council and chair GSI Scientific Council], Chalmers Univ. of Technology, Göteborg (Sweden) – until 05/2024 ;
G. Aarts, Swansea University (United Kingdom) – until 04/2024; N. Alahari, GANIL, Caen (France); M. Aliotta, University of Edinburgh (UK); M. G. Bisogni, University Pisa, INFN (Italy) - since 05/2024, G. Bollen, Michigan State University (USA); S. Chattopadhyay, VECC (India) – since 05/2024; E. Elsen , DESY, Hamburg, and FIAS, Frankfurt (Germany) – until 04/2024; B. Erazmus, Subatech Nantes (France); W. Florkowski, Jagellonia University (Poland) - since 05/2024; P. Gianotti, INFN Frascati (Italy); B. Ketzer, University Bonn (Germany) – since 05/2024, S. Le Pape, LULI, Ecole Polytechnique, Palaiseau (France) – since 04/2024; K. Parodi , Ludwig-Maximilians-University Munich (Germany) – until 04/2024; A. Roy, Inter-University Accelerator Centre New Delhi (India) – since 12/2024; Y. P. Viyogi , Variable Energy Cyclotron Centre, Kolkata (India) – until 04/2025.

Scientific Secretary: Carlo Ewerz / Monica Wamers (since autumn 2024)

Scientific and Technical Council / Wissenschaftlich-Technischer Rat (WTR), GSI

B. Lommel [Spokesperson], F. Herfurth [Vice-Spokesperson]; R. Aßmann; C. E. Düllmann; H. Elfner; M. Gorska-Ott; C. Kausch; K. Knie; H. Kreiser; M. Lestinsky; S. Menke; K. Peters; S. Reimann; U. Scheeler; C. Scheidenberger; M. Schwickert; H. Simon; P. Spiller; T. Stöhlker; J. Stroth; M. E. Toimil Molares; A. Vink; G. Walter; A. Wilms.

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S. Galès [chair], Laboratory of the Physics of the two Infinities Irène Joliot-Curier (IJCLab) (France) (up to 11/2024);
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Scientific Secretary: Karin Füssel.

12.2 Organisational charts

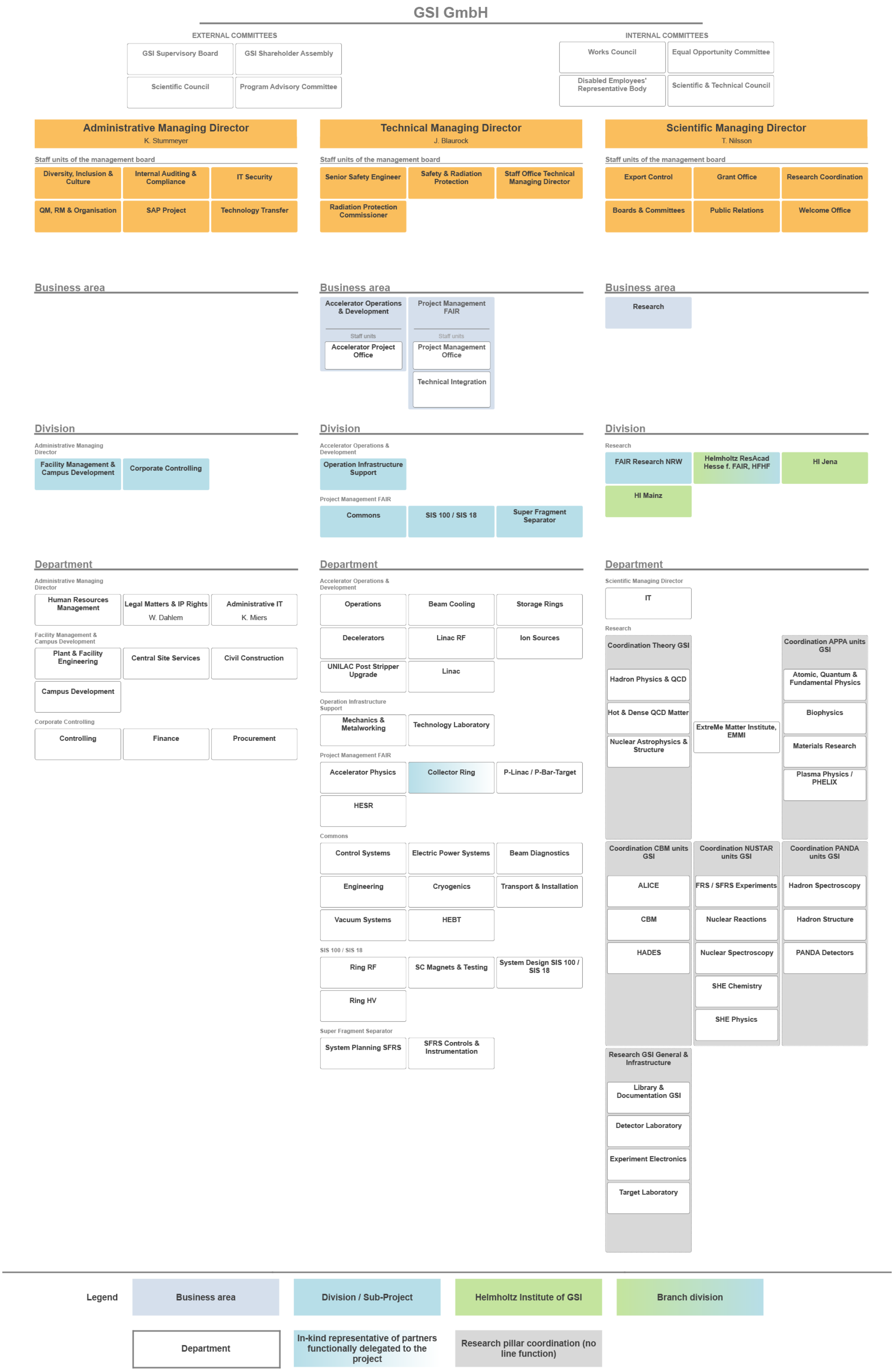

Figure 118: GSI organigram.

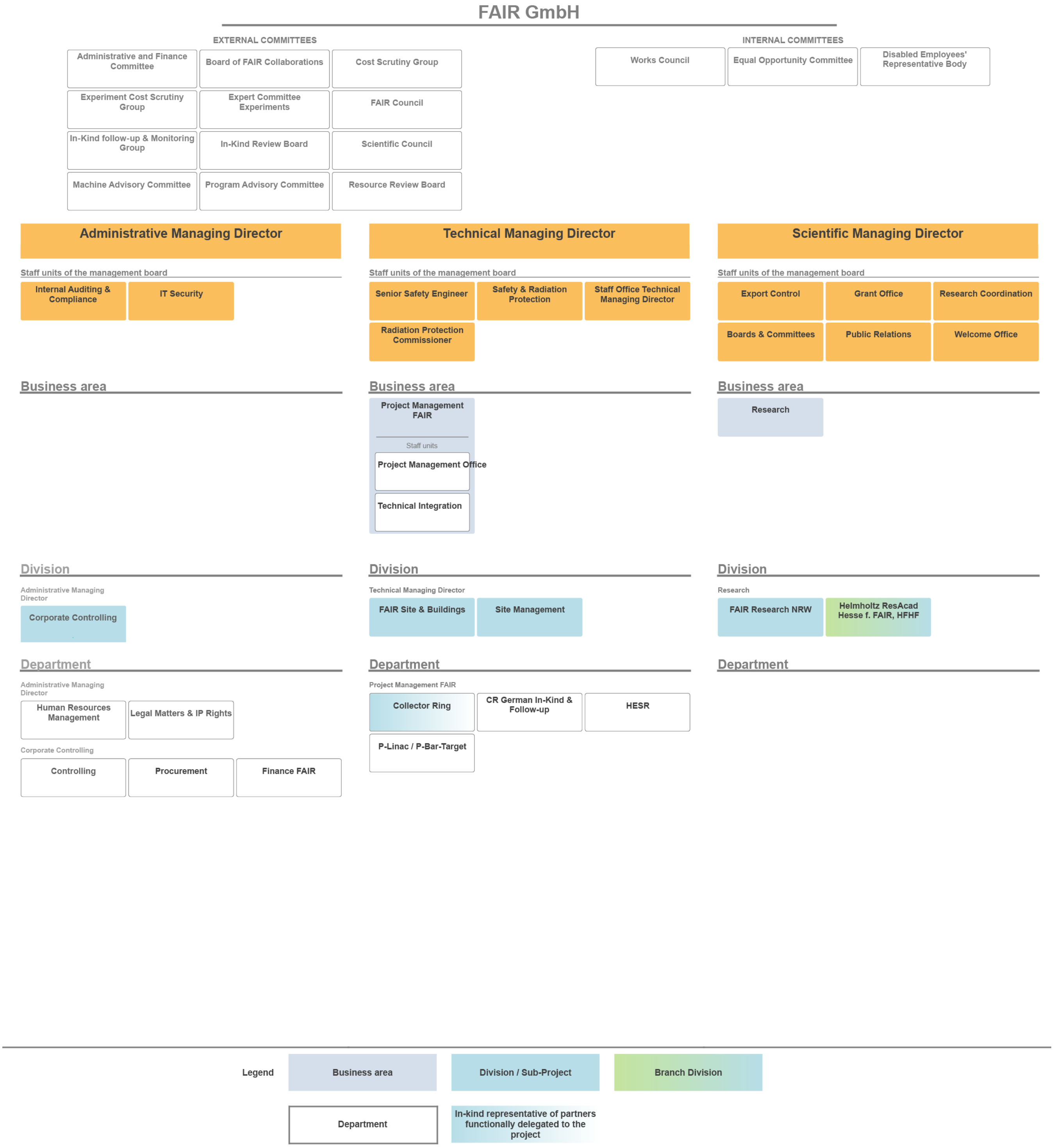

Figure 119: FAIR organigram.

GSI is a member of the largest national non-university science organization, the Hermann von Helmholtz Association of German Research Centers (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 Federal Ministry of Education and Research (BMBF), 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.