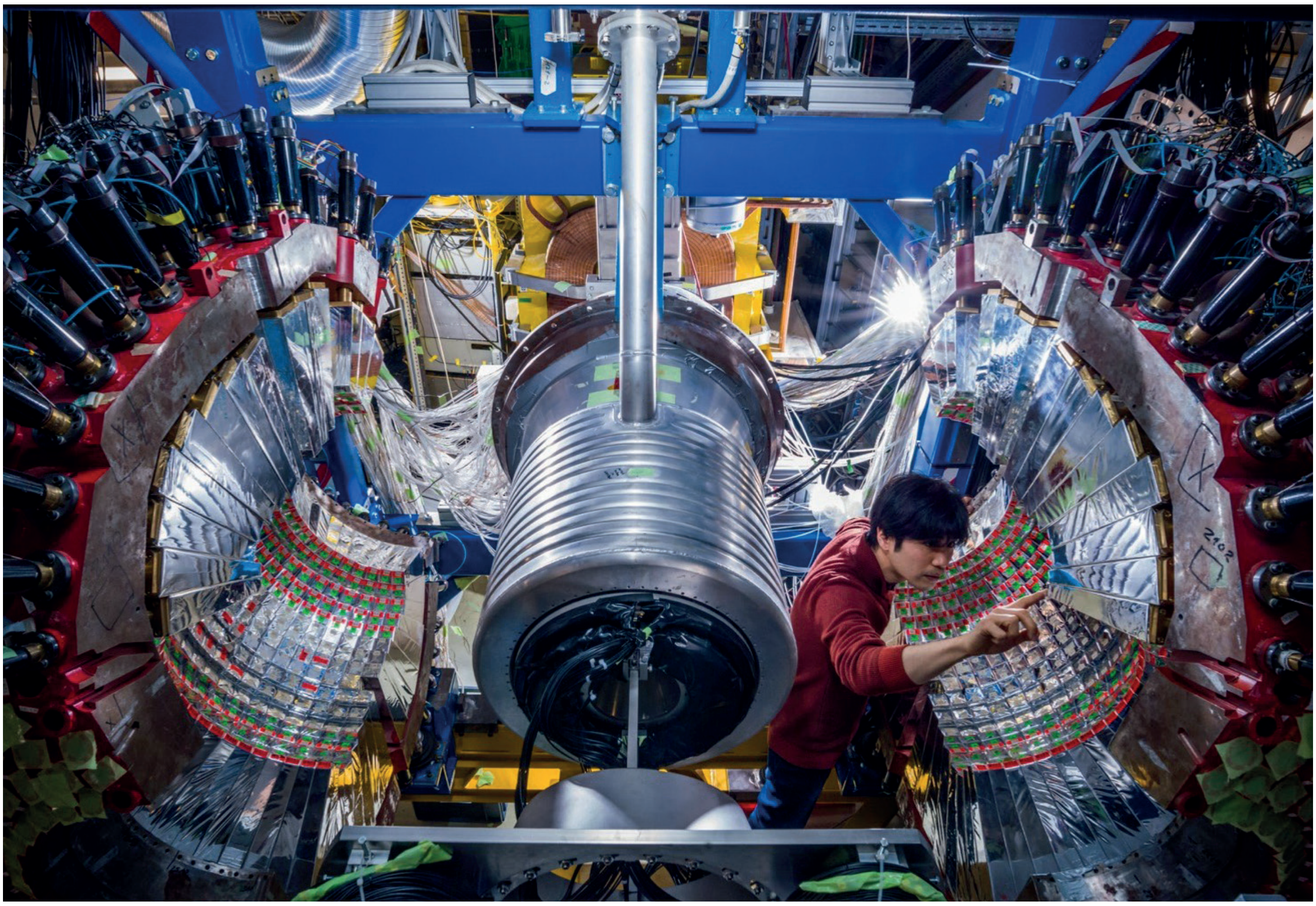
GSI REPORT 2023-1

GSI-FAIR SCIENTIFIC REPORT 2022

An overview of the 2022 achievements in science and technology



FAIR Phase-0 Research Program

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

The picture shows the WASA detector at the FRS mid-focal plane. It was used in pilot experiments of the Super-FRS Experiment Collaboration, in which a novel spectroscopic method was explored, coupling the WASA detector with the FRS high-resolution momentum spectrometer. The experiments conducted in 2022, proposed by Japanese colleagues, aimed at studying hypernuclei and searching for eta'-mesic nuclei. These topics are among the 3 top priorities of the NUSTAR Collaboration. The roughly 10,000 electronic channels of the 18-ton detector setup, including a super-conducting solenoid magnet, produced a data stream of about 300MB/s; the data are now being analyzed.

Photograph: J. Hosan, GSI/FAIR

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Imprint

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Coordination: Prof. Dr. Karlheinz Langanke (Technische Universität Darmstadt & GSI)
Deputies: Prof. Dr. Thomas Stöhlker (Universität Jena & Helmholtz Institute Jena & GSI),
Dr. Yvonne Leifels (GSI)

1.1 Research and technical developments at GSI/FAIR

Head: Prof. Dr. Karlheinz Langanke (Technische Universität Darmstadt & GSI)
Author: Yvonne Leifels

Only a few days after the beam time 2022 has started, the scientific community was caught off guard by the news of the Russians invading Ukraine. Suddenly, science that acted often as a bridge between conflicting countries and different cultures was disrupted. Within a week, cooperation with Russian institutions was shut down and participations of scientists with an affiliation of a Russian institutions in the international GSI/FAIR collaborations were frozen. The stay of Russian scientists at GSI was abruptly terminated, whereas Ukrainian colleagues worried about their families back home. GSI is participating in an initiative of the Helmholtz Association, which has the goal to support stays of Ukrainian scientists in Germany.

As a reaction of the Russian invasion, GSI followed the guidelines of the German Ministry and the recommendations of the alliance of German science organizations and suspended all cooperation and collaborations with Russian and Belarussian institutions. This has serious consequences and leads to a number of uncertainties in the work at FAIR and GSI. The GSI management has setup a "Task Force Ukraine" with the aim to carefully analyze the respective situation and help the employees and organizational units in the best possible way.

It was possible to compensate the shortfall of scientists from Russian and Belarussian institutions during the beam time campaign, such that most of the experiments could be continued without major problems. However, the collaboration stop with Russian institutions has partially severe impact on the completion of work from past experiments and the preparation of new experiment proposal. In addition, several obstacles are expected in the development and construction of FAIR accelerators and detectors. A working group of the FAIR project together with members of the FAIR collaborations has evaluated the consequences of the sanctions and a potential Russian failure to deliver components. Apart from lacking cash contributions, accelerator and detector components have been identified, which needs finding of alternative vendors and subsequent re-procurement. Fortunately, no component has been identified which could not be produced elsewhere. The FAIR collaboration might suffer a loss of approximately 400 participants with affiliations of Russian institutions. This loss affects the various FAIR collaborations quite differently, whereas it has only minor impact on BIOMAT and SPARC, the consequences for HED@FAIR, CBM and PANDA are more serious, and also some NUSTAR collaborations will have to take measures to replace the Russian contributions, if in-kind contributions will not be delivered.

The Corona pandemic, inflation, the shortage of raw materials, longer delivery times and the rise of energy costs lead to considerable additional financial requirements for the FAIR project. The FAIR management informed the shareholders in 2021 about the expected additional requirements. In February 2022, the Russian invasion into Ukraine and the suspension of the cooperation with Russian institutions became an additional important risk factor. The FAIR Council and the Federal Ministry for Research BMBF commissioned an external assessment of the additional costs and a scientific review to assess the potential of the FAIR science and identify potential intermediate step before completion of the intermediate objective IO. The team of external experts was headed by the experimental particle physicist Professor Rolf-Dieter Heuer, who was director-general of the European Organization for Nuclear Research CERN for six years, and the experimental physicist Professor Robert Tribble, deputy director for science and technology at Brookhaven National Laboratory, USA. The committee consisted of renowned experts, who have been assessing the project in great detail since April 2022. The in-person meeting of the Committee for First-Science and Staging Review of the FAIR Project Scientific Review, the FAIR management and representatives of the FAIR collaborations took place at GSI on 24./25. June 2022. The FAIR collaborations presented an overview on their science case, selected highlight topics, and the status of their detector set-ups. The report of the committee was finally issued to the FAIR Council in October 2022. The committee suggests a stepwise approach for the realization of the project, bringing the facility progressively into operation. It has also recognized that, as a consequence of various unforeseeable developments additional costs are unavoidable to reach the first step of viable operation.

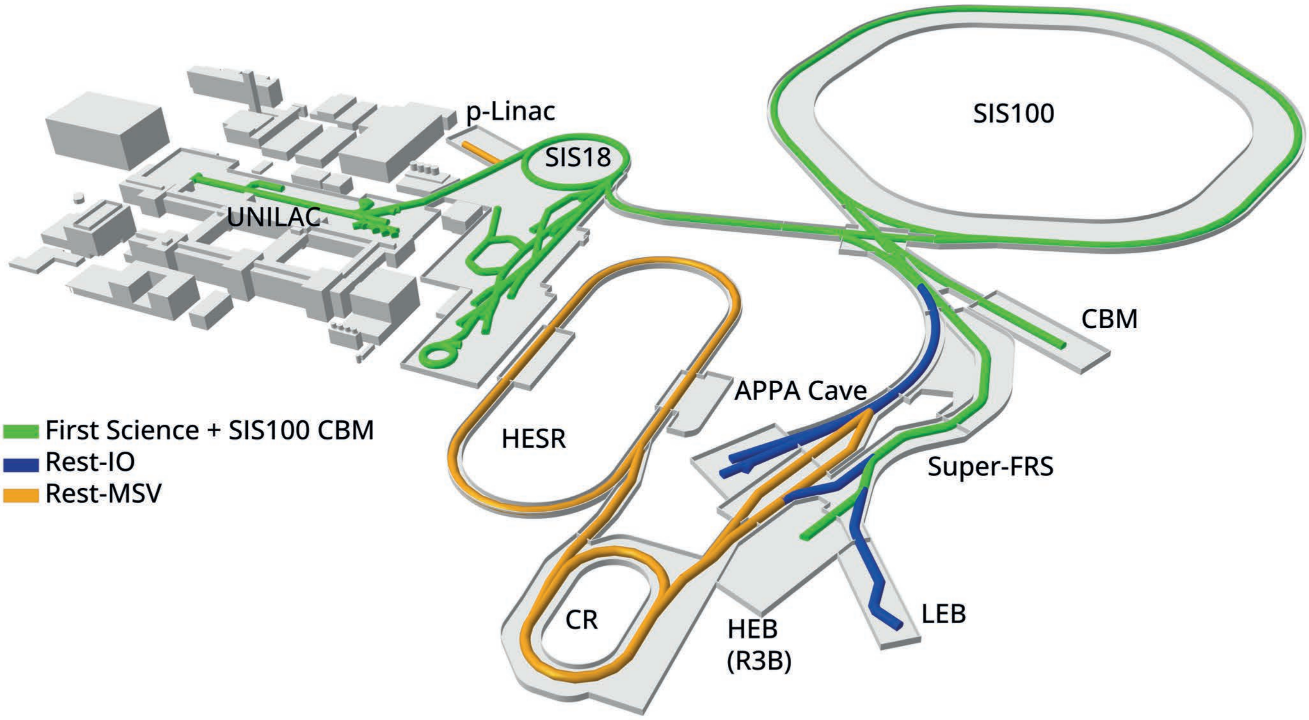

Figure 1. Scenario recommended by the Scientific Review panel towards FAIR intermediate objective (IO) and MSV.

The committee identified the taking into operation of the S-FRS with SIS18 beam followed by experiments in the NUSTAR high energy cave (HEB) as viable first step (Early Science). Completion of SIS100 has the next highest priority which would allow to provide beams into the S-FRS, the HEB cave (First Science), plus the CBM cave (First Science +). Completing the infrastructure and instrumenting the APPA cave should have priority over instrumenting the additional area in LEB for NUSTAR. In addition, the committee recommended that a time frame should be implemented for the finalization of the FAIR Modularized Start Version (MSV).

The complete report of the Scientific Review panel is available at the web site of GSI. In an extraordinary meeting of the FAIR council in Octobers, the shareholders endorsed the report and decided to develop a plan on how to finance the first realization steps.

GSI is a user facility and one of its key missions is to offer users from all areas of research the opportunity to perform scientific experiments, even under the current difficult conditions; this remains a fundamental commitment of the laboratory. The experimental opportunities offered by the FAIR Phase-0 scientific program has proven to very successfully attract large fractions of the FAIR scientific communities. The calls for the next two years of running have again seen an overwhelming response, with close to 1800 participants from 45 countries as co-authors of the 124 proposals, of which 58 have been submitted to the G-PAC, 24 to the MAT-PAC, 28 to the Bio-PAC, and 14 to the PPAC. In total 3,309 shifts of beam time (shift = 8 hours) were requested. The average overbooking factor was 2.9. The evaluations of the different sub-PAC committees and the G-PAC took place in person in autumn 2022.

The scientific and technical departments had to deal with the rise in costs for energy and materials and long delivery times for goods. In addition, it is expected that the personnel costs will rise substantially beyond the multi-annual financial planning of GSI. Therefore, it was decided in fall 2022 to shift the next user beam time, which was originally planned for the fall of 2023, to the beginning of 2024. Only an engineering run will be performed in 2023.

With the start of the POFIV period on the 1. January 2021 GSI has returned to the goals and procedures of program oriented funding and contributes to the following the programs "Matter and Universe" and "From Matter Materials and Life" with its FAIR oriented research program (LKI) and its facilities (LKII), as well as to the program "Matter and Technologies" (LKI).

Results and achievements of “Cosmic Matter in the Laboratory” are described in the chapter on NUSTAR, CBM, PANDA and Theory, where the program “From Matter to Materials and Life” is followed by APPA. Recent developments at the accelerators of the LK2 ion facilities are described in the chapter “Accelerator operation” and the experiments in the contributions of the respective departments. “Matter and Technology” achievements are described not only in chapter “Research in accelerators, detectors, electronics and IT” but also in “Accelerator operations”.

The Helmholtz Institutes (HI) Jena and Mainz were founded more than ten years ago as branches of GSI on the campus of the Friedrich Schiller University (FSU) in Jena and the Johannes Gutenberg University (JGU) in Mainz. Their Scientific Reports can be found on the homepages of the institutes.

1.2 Beamtimes for scientific experiments in 2022

Author: Daniel Serverin

Proposal number	Experiment topic	Spokesperson	Main Shifts	Parastitic shifts
E153	Multielectron recombination processes in He-like oxygen at the CRYRING@ESR electron cooler	Weronika Biela	20	
E141	Investigating the destruction of deuterium during the Big Bang using CARME@CRYRING	Carlo Bruno	32	
E128	Dielectronic recombination-assisted laser spectroscopy: a new tool to investigate the hyperfine-puzzle in $Bi^{80+;82+}$	Wilfried Nörtershäuser	10	
E142	Nuclear Hyperfine Mixing in ${}^{229}Th^{89+}$ - storage ring studies of an orders-of-magnitude accelerated nuclear decay	Carsten Brandauer	31	
E146	Indirect measurements of neutron-induced reaction cross sections at storage rings	Beatrice Jurado	15	
CMAT*	Materials Science at the CRYRING	Christina Trautmann (GSI)	21	
S447	Studies of the d+π- signal and lifetime of the ${}^{3}_{\lambda}H$ and ${}^{4}_{\lambda}H$ hypernuclei by new spectroscopy techniques with FRS	Takehiko Saito	20	
S450	Study of N=126 nuclei: isomeric and beta decays in ${}^{202}Os$ and ${}^{203}Ir$	Zsolt Podolyak	17	

S483	Testing of beam instrumentation equipment for the Super-FRS at FAIR	Chiara Nociforo (GSI)	7	
S488	Understanding liquid-liquid phase transformations by temperature-dependent viscosity measurements at high pressures using high energy proton microscopy	Börn Winkler		18
S489	First combined laser-ion experiments at SIS-18	Vincent Bagnoud (GSI)		29
S490	Search for η'-mesic nuclei in C12(p,dp) reaction	Kenta Itahashi	15	
S497	Test of the beam tracking and identification for HISPEC-10	Jelena Vesic	1	
S505	Investigation of the beta-strength crossing N=126 and the formation of the 3rd r-process abundance peak	Jose L. Tain	15	
S509	Study of drip-line phenomena in neutron-rich nuclei	Olivier Sorlin	19	
S514	mCBM@SIS18	Norbert Herrmann	13	
S518	HADES III: Electromagnetic transition form factors of strange hyperons	Joachim Stroth (GSI)	72	
S522	First characterization of Short-Range Correlations in exotic nuclei at R3B	Anna Corsi	21	

SBIO*	Biophysics experiments at SIS18 including experiments for ESA	Michael Schoz (GSI), Christian Graeff (GSI)	25	
SMAT*	Materials research experiments at SIS18	Christina Trautmann (GSI)	13	
U316	Test of calorimetric low-temperature detectors (CLTDs) for the detection of heavy ions at intermediate and high ion energies for application in NUSTAR	Saskia Kraft-Bermuth	6	
U319	Discovery and Spectroscopy of Neutron-Deficient Pu Isotopes and their Alpha-Decay Daughters	Daniel Cox	11	
U321	Laser spectroscopy of fermium, nobelium and lawrencium around N=152	Sebastian Raeder (GSI)	70	26
U323	Study of the multinucleon transfer process in the reactions ^{136}Xe+^{192}Os and ^{136}Xe+^{197}Au	Emanuele Vardaci	11	
U326	Plasma Stripper: Investigation of charge state and energy loss of heavy ions after interaction with inductively coupled plasma	Joachim Jacoby	22	
U317	Chemical studies of the superheavy element Z=115	Alexander Yakushev	36	
UMAT*	Materials research experiments at UNILAC	Christina Trautmann (GSI)	36	120

Table 1. List of user experiments in 2022 and accounted beamtime in 8h shifts. Secondary beam users get on the average 10 % of the available beam.

* Collective designation for several experiments.

Experiments in 2022

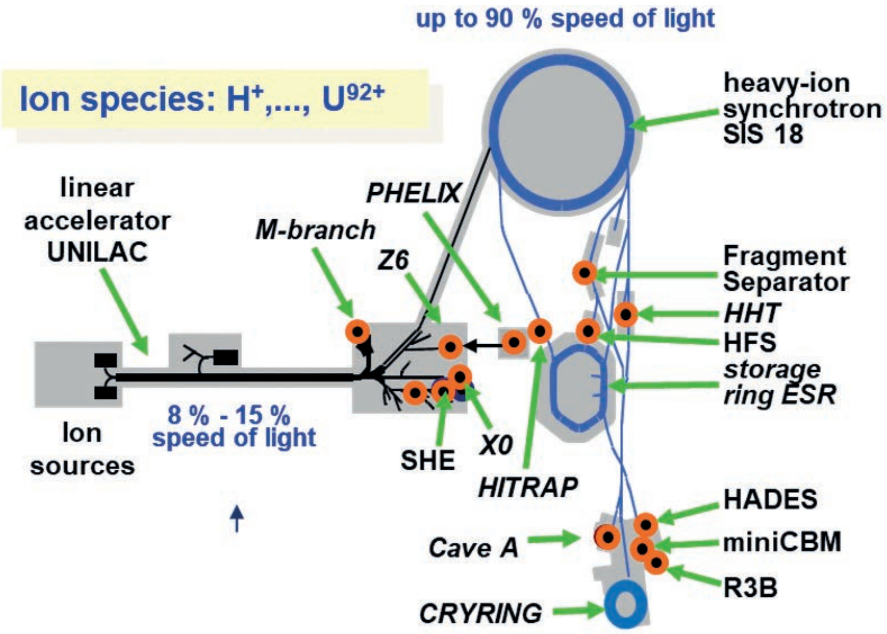

Figure 2. Overview of the experimental facilities for GSI. Facilities for the program “From Matter to Materials and Life” are depicted in italics.

The physics beamtime period 2022 started beginning of February with a light ion-beams block (1-H, 6-Li, and 12-C) serving mainly HADES, WASA set-up at the mid-focal plane of the FRS, and PRIOR. The UNILAC rf level limitation exclude a parallel UNILAC experiment program. Nevertheless, a physics run at CRYRING with local injector could be performed in parallel.

HADES (Exp. S518) was in total served over 4 weeks with a very stable Proton beam at 4.5 GeV. Unfortunately, the data rate suffered on micro-spill structure and an unforeseen beam halo effects. The WASA detector was used for the first time at GSI/FAIR. After a short commissioning block in parallel to HADES, two experiments (Exp. S490, S447) were successfully performed with ^{1}H and ^{6}Li beams respectively. PRIOR (Exp. 488) demonstrated its full performance running in parallel mode with a high intense proton beam at low repetition rate. Besides the main user program, FAIR S-FRS detector tests (Exp. S483), mCBM commissioning (Exp. S514), and R3B preparatory tests (Exp. S522) could be served in parallel with a ^{12}C beam. The experiment E141 used an ^{16}O beam from CRYRING’s local injector. After a challenging machine and internal target setup, first data could have been collected at the end of target commissioning.

After one-week conditioning of the UNILAC rf system for heavy ion operation, the second beamtime block started on 25th of March with ^{48}Ca, ^{238}U, and ^{56}Fe beams. While making use of the full parallel capability of GSI's accelerator facility, UNILAC, SIS, and ESR served up to seven experiments. At UNILAC, the Super Heavy Element (SHE) groups operated at SHIP (Exp. U319 + U321) and TASCA (Exp. U327) using the ^{48}Ca beam. In parallel, a minor materials research program at M-branch (UMAT) and an UNILAC plasma physics experiment (Exp. U326) was carried out.

At SIS18, the ^{238}U and ^{56}Fe beams were used by mCBM (Exp. S514). Furthermore, a biophysics (SBIO) and materials research (SMAT) program was performed in Cave A and M including a dedicated ESA block for biology and electronic component tests. In parallel, the ^{238}U beam was delivered to HHT for the plasma physics HIHEX experiment. Here, phase transitions were studied with a highly focused ion beam in combination with the PHELIX laser beam (Exp. S489).

At ESR the ^{238}U beam was decelerated and delivered to Cave A for a channeling experiment (Exp. E137). Unfortunately, the experiment had to be canceled due to machine problems at UNILAC that made it impossible to operate the U-beam. After repair of the UNILAC, the ^{238}U beam was utilized at ESR to produce a ^{229}Th beam for hyperfine mixing studies.

Beginning of May, the physics beamtime was continued, after a maintenance break and a 10-days machine studies block. A heavily loaded experimental program with a very high degree of parallel operation characterized the second part of the beamtime 2022.

At UNILAC, experiments received an intense 48-Ca beam for materials research and SHE-physics (Exp. U321). In addition, the Ca beam was delivered for experiments on detector developments for NUSTAR (Exp. U316) and CBM (Exp. U514) and for a plasma physics run (Exp. U326). A ^{197}Au beam for a materials research program and ^{134}Xe for a NUSTAR experiment on multi-nucleon transfer reactions (Exp. U323) accomplished the UNILAC beamtime.

Meanwhile, SIS18 provided ^{208}Pb beam for two DESPEC run (Exp. S450, S505) and another plasma physics HiHEX experiment at HHT (Exp. S489). Two experiments of the R3B collaboration (S522 and S509) could be successfully finished with ^{18}O and ^{40}Ar beams via the FRS as well as a short biophysics program with ^{12}C beam. Furthermore, several short detector tests (S483, S497, S506) could be scheduled in parallel to the main program. mCBM at HTD (Exp. S514) finalized its experimental campaign with ^{58}Ni and ^{197}Au beams.

The ESR program started with a ^{209}Bi beam for the experiment E128. Unfortunately, technical problems at ESR injection prevented a timely start. Nevertheless, thanks to great efforts of all involved operating teams, it was possible to re-schedule the experiment, which was successfully finished end of May. In between, the commissioning of the HITRAP facility took place using a ^{58}Ni beam from ESR. Afterwards, a combined ^{197}Au block at ESR-CRY was dedicated for machine studies and to extract the beam for experiments of materials research. The newly installed materials research target station at CRYRING was operated for the first time. The experiment E146 using a ^{208}Pb beam at ESR complemented the storage ring program of the beamtime block.

2. Research of the APPA Departments

Coordination: Prof. Dr. Thomas Stöhlker (GSI/Helmholtz-Institut Jena)
Author: Thomas Stöhlker

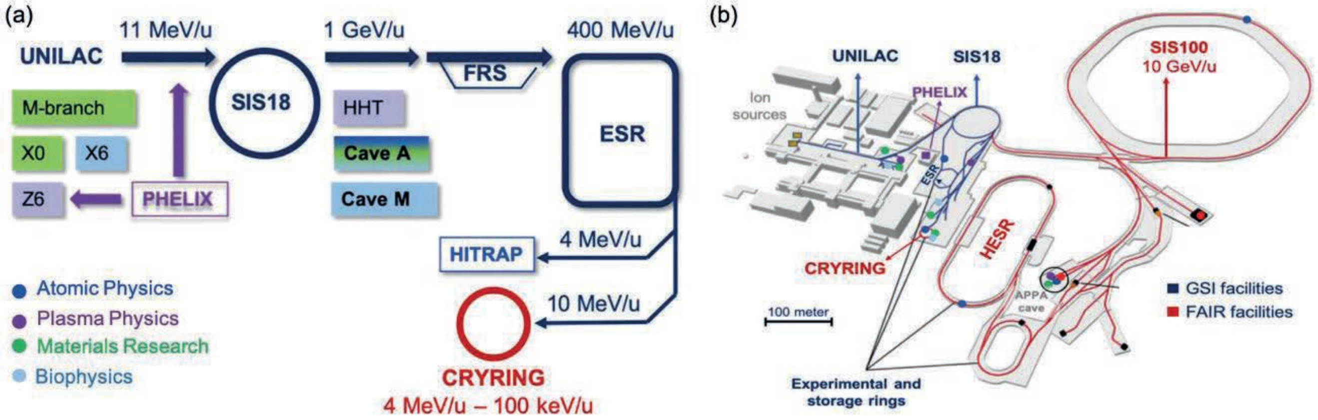

Figure 3.(a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (Th. Stöhlker et al., Nucl. Instr. Meth. B 365, 680 (2015))

At GSI, the research departments Atomic, Quantum, and Fundamental 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 allow the MML/APPA community to address most challenging questions at the frontiers of modern research (MML/APPA research at GSI contributes to all three research topics of the program MML).

Figure 3 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 (left side of Figure 3) are in user operation. The 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 the FAIR Phase-0, GSI offers 3 months/year of beam time. The national university partners are funded through the BMBF ErUM framework program, including the research priority program APPA [1]. GSI-MML scientists support users throughout the entire process, including the preparation and execution of the beam times, data storage and analysis as well as the interpretation and publication of obtained physics results.

2.1 Atomic, Quantum, and Fundamental Physics

Head: Prof. Dr. Thomas Stöhlker, GSI & HI-Jena, Friedrich-Schiller University Jena
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In close cooperation with scientists from all over the world, and especially within the framework of the SPARC collaboration (see Figure 3), 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. In this context, the storage ring / ion trap complex ESR / CRYRING@ ESR / HITRAP, which is part of the modularized start version of the FAIR facility, offers fascinating, worldwide unique possibilities by providing cooled heavy ion beams, for basically all elements (from hydrogen to uranium) in every high charge state up to fully ionized uranium. A particular unique selling point of the ESR / CRYRING@ESR / HITRAP complex is that cooled ions can be provided over a wide energy range from nearly at rest in the laboratory all the way up to relativistic velocities of approx. 70% speed of light. In the future HESR storage ring, the energy range will be further extended to highly relativistic energies (γ-factor up to 6), which will provide up to now unprecedented, unique research opportunities. Finally, the combination with the fragment separator (FRS) allows us to include short-lived nuclides into the research spectrum. Altogether, these unique and highly relevant research opportunities enable a breadth 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 (approaching 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 accomplish ambitious research goals, particular important activities of the AQF 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 are adjusted to ensure optimal use of the above-mentioned research infrastructures.

In 2022, emphasis was given to physics production runs at the GSI/FAIR storage rings ESR and CRYRING@ESR (Swedish in-kind contribution to FAIR) by exploiting dedicated FAIR instrumentation developed by the SPARC collaboration. Note that in 2020, both rings have been commissioned (CRYRING@ESR) or broad back into operation after a very long shutdown period (ESR). Both machines are now equipped with the FAIR control system and are fully operational. The storage and cooling of high-Z ions at highest charge state and of secondary beams, along with sophisticated beam manipulation procedures such as deceleration or accumulation, are now routinely available. This is more than encouraging news for the midterm perspectives for the Atomic, Quantum, and Fundamental Physics department and the related research activities of the SPARC collaboration. These achievements could only be possible thanks to extraordinary engagement of the various local GSI teams (e.g. the ESR team, the CRYRING team, the Commons division, and the members of the AQF department).

In the following we concentrate on the research achievements of the Atomic, Quantum, and Fundamental Physics department/ SPARC collaboration obtained within the framework of FAIR Phase-0. For further important research activities conducted at external facilities (e.g. CERN) we refer to the selected references at the end of this section. Note that in all 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 took the lead (for the annual report of HI-Jena, please check out Annual Reports of the Helmholtz-Institut Jena.

Highlights in 2022

Highlights and achievements of the beam time

During the reporting period the focus of activities was devoted to beamtimes in 2022 at the storage and trapping facilities of GSI/FAIR (ESR, CRYRING and HITRAP) which lasted from March 2022 through June 2022. At CRYRING@ESR, the activities concentrated on the commissioning and on very first experiments with the CARME reaction spectrometer along with the newly installed internal target in connection with the operation of the local ion source and the local injector. The demands for the later installations and in particular for the ion sources are steadily increasing and will in future require substantial additional resources in terms of personnel and investments in order to meet the needs of the users. A further very important center of activities was assigned to experiments at the ESR storage ring, taking into operation novel FAIR instrumentation indispensable for pushing towards novel classes of experiments, like e.g. the exploration of QED in the extreme field domain via exploiting stored and cooled secondary ions. Finally, a particular emphasis was given to the re-commissioning of the HITRAP facility. HITRAP is a Helmholtz high priority project which is financed by Helmholtz funds. It was taken out of operation in 2014 without having served any experiment. HITRAP is a worldwide unique facility aiming at extending high-precision experiments at storage rings for ions at highest charge states into the regime of ultimate precision.

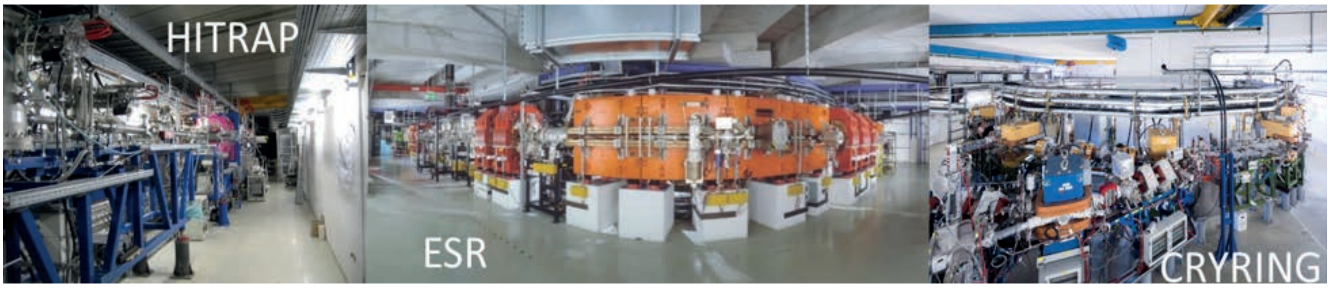

Figure 4. The storage and trapping facilities HITRAP, CRYING@ESR, and ESR are fully operational or under commissioning.

Towards first experiments at HITRAP

Within a machine time from May 17th to 28th 2022, the HITRAP facility had a further commissioning round utilizing highly charged nickel ions from the ESR storage ring. The HITRAP physics program and the status of the facility were discussed at a dedicated EMMI workshop in Eisenach from July 17th to 20th with 60 participants. In preparation for future beamtimes, the ARTEMIS experiment, aiming at testing bound-state quantum electrodynamics with trapped highly charged ions, is being commissioned with Ar^{13+} ions from an offline source. The connection of the ARTEMIS setup to the low-energy beamline of HITRAP has been successfully established recently. A new superconducting magnet, which is a Swedish in-kind-contribution within FAIR/SPARC, for an upgrade of the SPECTRAP experiment has been installed at the HITRAP platform. The existing setup of SPECTRAP is being adapted to the new magnet and commissioned with offline ions.

Laser spectroscopy of $^{229}Th^{89+}$ using nuclear hyperfine mixing at the ESR: towards the nuclear, optical frequency standard

Thorium-229 is the only known candidate for a frequency standard based on a nuclear transition [1]. Such a “nuclear clock” can be used for ultra-precise metrology, enhanced precision in GPS and geodesy or as a means to find answers to very fundamental questions in science. At GSI, an inimitable approach to the physics of ^{229}Th is currently being pursued. It is based on an effect that is unique to very highly charged ^{229}Th such as one-electron $^{229}Th^{89+}$: In addition to the ordinary hyperfine structure, the very strong magnetic field of ~28 MT of the unpaired s-electron causes mixing of the F = 2 levels of the ground (g.s.) and isomeric states (i.s.). The mixing yields an additional small energy shift.

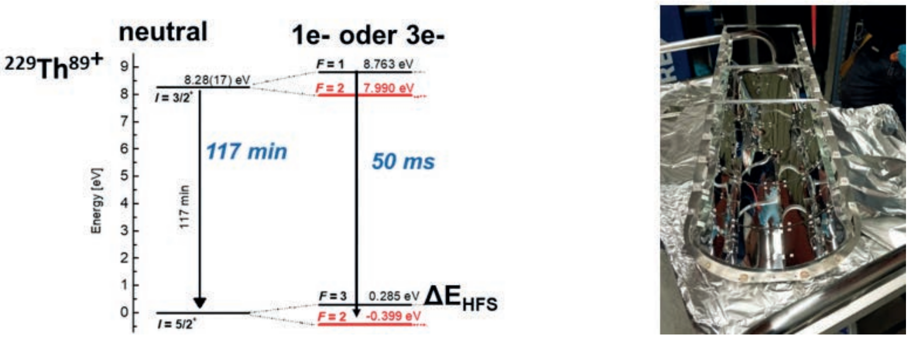

Figure 5. (left) H-like $^{229}\mathrm{Th}^{89+}$: Acceleration of nuclear decay by coupling of electrons to nuclear spin (hyperfine interaction. (right). Novel in-ring VUV fluorescense detection system $\mathrm{MgF_2}$-coated Al-mirrors for the detection of photons bellow 115 nm (Collaboration Fraunhofer IOF, Jena).

But more notable, the lifetime of the i.s. decreases drastically by 5-6 orders of magnitude, from a few hours down to a few 10 ms. In essence, depending on the electronic configuration, the lifetime of the nucleus can be gradually or instantaneously manipulated on purpose. Furthermore, the vastly accelerated decay, e.g., in $^{229}\mathrm{Th}^{89+}$ implies that the excitation probability with a laser and the detection of fluorescence light are each enhanced by these 5-6 orders of magnitude. Utilizing these unique assets of nuclear hyperfine mixing (NHM), in April 2022 a first attempt to laser-excite the $^{229}\mathrm{Th}^{89+}$-isomer at the storage ring ESR was performed (experiment E142). Although, the $^{229}\mathrm{Th}$ laser resonance could not be found yet—mainly due to rather poor experimental conditions predominantly from the accelerator side—large progress could be achieved: $^{229}\mathrm{Th}^{89+}$ ions were cleanly separated in the ESR, an over-worked fluorescence detection region optimized for the short wavelengths of the $^{229}\mathrm{Th}^{89+}$ NHM-transitions was successfully commissioned, experimental procedures and the DAQ were adopted to the low beam intensities, and the general feasibility of storage-ring laser experiments with inevitably low intensity secondary (radioisotope) beams was demonstrated.

Direct observation of the ground state hyperfine splitting of hydrogen-like $^{208}\mathrm{Bi}^{82+}$: first laser excitation of an in flight produced isotope in ESR

About 20 years ago, the so-called specific difference between the ground state hyperfine splittings in hydrogen- and lithium-like ions was proposed as a tool to test bound-state QED in the strongest electromagnetic fields presently available in the laboratory [2]. Surprisingly, our measurements of these transitions in $^{209}\mathrm{Bi}$ by laser spectroscopy at the ESR [3,4] in the last decade revealed a deviation of the specific difference by 7σ from the latest theoretical prediction. This large discrepancy between experiment and theory—also known as the hyperfine puzzle—was, however, resolved through a new measurement of the nuclear magnetic moment in $^{209}\mathrm{Bi}$. Here we report on our beamtime (E128) carried out at the ESR in May 2022. We succeeded to produce and separate a sufficient amount of $^{208}\mathrm{Bi}^{82+}$, about 10^5 ions, and to observe for the first time a laser resonance signal for an accelerator-produced isotope in a storage ring. The UV fluorescence of this hydrogen-like ion was found close to the expected rest-frame value predicted [5]. The experimental observation of this hyperfine line is an important step towards the determination of the specific difference of $^{208}\mathrm{Bi}$, which can provide one of the most stringent tests of strong-field bound-state QED in the magnetic sector.

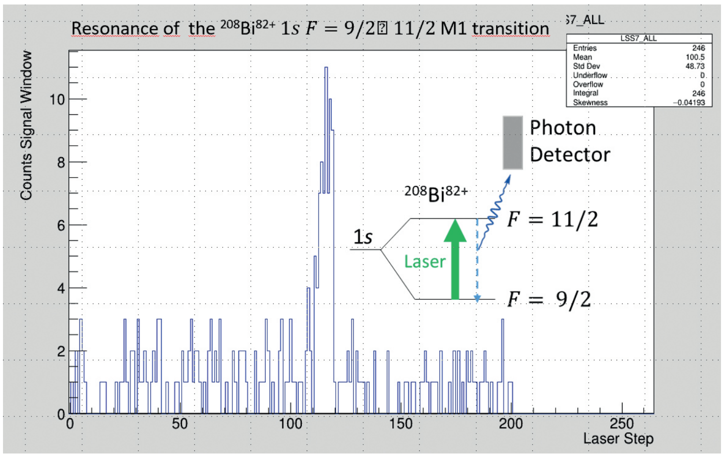

Figure 6. Online (preliminary) UV fluorescence spectrum observed for laser excited of $^{208}\mathrm{Bi}^{82+}$ in flight produced hyperfine states (W Nörtershäuser, R. Sanchez et al.).

First measurements with the novel CRYRING@ESR internal target

The upgrade of the internal target station at the ESR and its successful operation during numerous beamtimes led to the development of an overall re-design of the internal target inlet chamber, intended for the use at the current and future storage rings [6,7]. The assembly of the new inlet chamber at the experimental section YR09 of the CRYRING@ESR started 12 months ago as a part of the entire internal target installation. The subsequent commissioning of the internal target was done in the course of the CARME experiment beamtime in early 2022. Due to unresolvable issues regarding the realization of an operational helium target, the experiment had to be conducted with a nitrogen target. After several improvements of the internal target, the setup had been completed on the basis of the experience gained during the commissioning, and a second internal target experiment was performed within the scope of a machine beamtime. This second beamtime was dedicated to measurements aiming at the characterization of the target properties and investigation of capture processes of highly charged ions (Au^{78+}) interacting with light target atoms (He) in the low energy regime of the CRYRING@ESR, namely 10.1 MeV/u and 4.8 MeV/u.

The first nuclear reaction measurements on the CRYRING using the CARME chamber

Storage rings present a new and unique opportunity to solve long standing problems in astrophysics by performing nuclear reaction measurements with stored radioactive isotope beams (RIB) incident upon an ultra-thin internal gas-jet target. The CRYRING@ESR storage ring, part of FAIR Phase-0, is unique worldwide in allowing heavy RIBs to be decelerated, cooled, and circulated at energies of astrophysical interest. The recently installed and commissioned CRYRING Array for Reaction Measurements (CARME) chamber [8] utilizes this novel methodology and will be used to study direct nuclear reactions at stellar energies in addition to indirect studies of key nuclear properties with consequences for both quiescent and explosive astrophysical environments from the Big Bang to Supernovae. The CARME chamber was mounted on the CRYRING in September 2021. High resolution (30 keV FWHM), highly segmented (128x128 strips) Double Sided Silicon Strip Detectors (DSSD) were installed in the chamber and proved that XHV pressures, required for the beam to circulate the storage ring, could be achieved with DSSD's, and the accompanying electrical cabling installed directly under vacuum with no windows or pockets. The DSSD's are capable of movement under XHV required for operation on storage rings. CARME was successfully commissioned using a deuterium beam on a nitrogen target in February 2022. This represented a major achievement as it was the first use of the internal gas-jet target, the first beam on target and the first observation of nuclear reactions at the CRYRING and acts as a launch pad for the exciting scientific program ahead. CARME is a significant part of the UK in-kind contribution to FAIR. CARME's science program will now by supported by the ERC-STG grant ELDAR, PI Carlo Bruno (U. Edinburgh).

X-ray emission associated with radiative recombination for Pb^{82+} ions at threshold energies

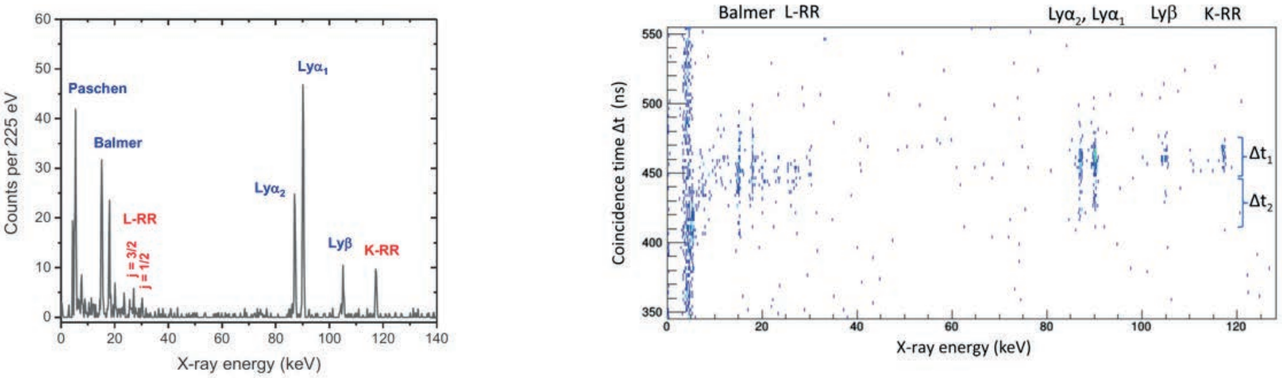

Figure 7. (left) X-ray spectrum measured at the observation angles of 0 deg a Ge(i) detector in coincidence with 10 MeV/u Pb^{81+} projectiles. X-ray energies are given in the laboratory frame. (right) Two-dimensional presentation of the coincidence time Δt versus the x-ray emission observed a 0 deg (laboratory frame). The coincidence time refers to the time difference between photon (start) and particle (stop) detections (relative timescale). $\Delta t_1 \approx 30$ ns refers to the cooler section; $\Delta t_2 \approx 40$ ns refers to the region outside the electron cooler [8].

For decelerated bare lead ions at a low beam energy of 10 MeV/u, the x-ray emission associated with radiative recombination (RR) at threshold energies has been studied at the electron cooler of the CRYRING@ESR [9]. In this experiment, we observed the full x-ray emission pattern by utilizing dedicated x-ray detection chambers installed at 0 deg and 180 deg observation geometry. Most remarkably, no line distortion effects due to delayed emission are present in the well-defined x-ray spectra, spanning a wide range of x-ray energies (from about 5 keV to 100 keV), which enabled us to identify fine-structure resolved Lyman, Balmer, and Paschen x-ray lines along with the RR transitions into the K, L, and M shells of the ions. For comparison with theory, an elaborated theoretical model is established taking into account the initial population distribution via RR for all atomic levels up to the Rydberg states with principal quantum number n = 165 in combination with time-dependent feeding transitions. Within the statistical uncertainty, the experimental data are in very good agreement with the results of rigorous relativistic calculations. Most notably, this comparison sheds light on the contribution of prompt and delayed x-ray emission (up to 70 ns) to the observed x-ray spectra, originating in particular from yrast transitions into inner shells.

Sympathetic cooling schemes for separately trapped ions coupled via image currents

Cooling of particles to mK-temperatures is essential for a variety of experiments with trapped charged particles. However, many species of interest lack suitable electronic transitions for direct laser cooling. We studied theoretically the remote sympathetic cooling of a single proton with a laser-cooled 9Be+ in a double-Penning-trap system [10]. We investigated three different cooling schemes and found, based on analytical calculations and numerical simulations, that two of them are capable of achieving proton temperatures of about 10 mK within cooling times on the order of 10 s. In contrast, established methods such as feedback-enhanced resistive cooling with image-current detectors are limited to about 1 K in 100 s. Since the studied techniques are applicable to any trapped charged particle and allow for a spatial separation between the target ion and the cooling species, they enable a variety of precision measurements based on trapped charged particles to be performed at improved sampling rates and with reduced systematic uncertainties.

Indirect measurements of neutron-induced reaction cross sections at the ESR

The instrumentation and methodology developed within AQF department and APPA/SPARC collaboration enables a wide range of cross-discipline experiments. In June 2022 we performed an experiment at the ESR (E146), where we used the ^{208}Pb(p,p') reaction as surrogate reaction for the n+^{207}Pb reaction. A ^{208}Pb^{82+} beam interacted with a hydrogen gas-jet target and we measured for the first time the probability that the excited ^{208}Pb decays by emitting γ-rays or a neutron. To achieve this with conventional methods is very complicated [11]. We took advantage of the capability of the ESR storage ring to separate the residues of ^{208}Pb formed after γ-ray and neutron emission. We could disentangle these residues from the huge Rutherford scattering background by detecting them in coincidence with the scattered protons, see the figure below. The measured decay probabilities will allow us to infer the neutron-induced radiative and inelastic cross sections of ^{207}Pb. This experiment opens the way to future measurements with short-lived nuclei, whose neutron-induced cross sections cannot be measured with standard techniques. The corresponding science program is supported by the ERC-AdG grant NECTAR, PI Beatriz Jurado (Bordeaux).

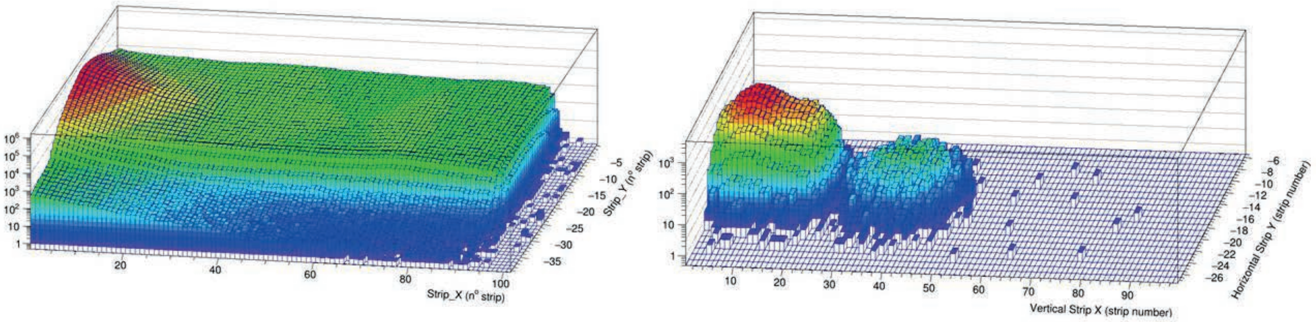

Figure 8. Measured position of beam residues without (left) and with (right) coincidence with the scattered protons. Right, the ^{208}Pb residues formed after γ emission build up the left bump, while the ^{207}Pb residues formed after neutron emission consti-tute the right bump.

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2.2 Materials Research

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The highly multidisciplinary activities in Materials Research in 2022 included projects with focus in physics, chemistry, materials science, astrophysics, geophysics, and biochemistry. During the beamtime block between March and June 2022, more than 30 different irradiation experiments were successfully performed using target stations at UNILAC (M-branch, X0), SIS18, and CRYRING. The investigations at the M-branch focused on sample irradiations combined with in situ and/or online analyses to study beam-induced effects and defect creation in minerals, high-entropy and carbon-based materials, and nanostructures. UNILAC beams also played an important role in simulating galactic cosmic radiation processes. Films of organic molecules present in space were bombarded with ions and analyzed in situ by infrared spectroscopy. Sputter yields and destruction cross sections were derived and serve as important input data for astrophysical models [1]. Simulation of cosmic radiation effects is also of great interest for electronic materials and devices for space applications. Radiation hardness tests were performed by various users, some of them at the heavy ion microprobe in combination with high precision targeting of specific chip locations, while other users conducted broad beam irradiations and analyzed offline structural changes and functional disorder [2]. Special efforts have been made to better understand ion-beam induced desorption processes of accelerator components, a topic of importance for the dynamic vacuum at SIS18 and future SIS100. In collaboration with the accelerator department, ionoluminescence and spectroscopic studies were undertaken for ZnO(In) as fast ceramic scintillator material [3] and for diamond, a candidate for detectors with excellent radiation hardness.

Regarding the nanoscience activities, UNILAC beams were applied to fabricate track-etched membranes and single-nanochannels. By combining single-nanochannels with various surface modification techniques, new biomimetic nanochannels for chemical and biological sensing applications were developed [4,5]. By electrochemical deposition in track-etched membranes, nanowire arrays and networks with tailored dimensions were synthesized and characterized for various energy applications such as thermoelectrics and electro-catalysis.

Our efforts to provide a sophisticated platform for irradiation and in situ characterization of materials under high pressure continued. The facility was upgraded with a remote-controlled beam collimator system, several goniometers for high-precision alignment of the diamond anvil cells and an online Raman spectrometer. The upgraded setup was successfully installed and operated during the last beamtime and allowed us to monitor in situ structural changes of pressurized minerals and nanowires irradiated with uranium ions.

Highlights in 2022

Simulation of sputtering processes of polycyclic aromatic hydrocarbons by cosmic rays

The rate of sputtering and release of condensed species at the very low temperatures prevailing in space is an important aspect of interstellar chemistry. If there were no such mechanism, the entire gas phase would have to condense in times shorter than the lifetime of dense interstellar clouds, but astronomers in turn are detecting many complex organic molecules in space. The recent discovery of cyclic aromatic molecules by radioastronomy challenges our understanding of desorption mechanisms, since the observed abundances are rather high. To simulate the interstellar cosmic ray impact contribution, sputtering yields and destruction cross sections were investigated for large carbonaceous species in the solid phase. Thin films of perylene and coronene were irradiated with 230 MeV $^{48}Ca^{10+}$ (UNILAC). The radiolysis destruction cross-section was deduced by in situ observation of the evolution of the infrared (IR) spectra of the bombarded films as a function of ion fluence (experimental setup: Figure 9 left). The GSI experiments were complemented by irradiations of films deposited on a quartz cell microbalance with 1.5 MeV N^+ ions (IJC Lab, Orsay). The recording of the mass loss as a function of fluence provided information on the sputtering rate (Figure 9 right). Combining these two results with the astrophysical spectrum of galactic cosmic rays helps to constrain the amount of species reinjected by sputtering of dust grains in astrophysical media [1].

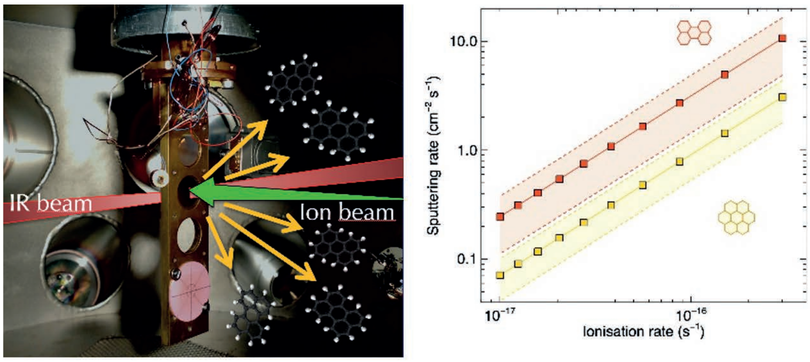

Figure 9. (Left) Irradiation chamber with perylene and coronene films as target. Under ion bombardment large molecules are sputtered from the surface. Simultaneous modifications of the films are monitored by IR spectroscopy. (Right) Calculated sputtering rate in the range of typical cosmic ray ionization rates (according to astrophysical models) for perylene (C_20H_{12}, in red) and coronene ($C_{24}H_{12}$, in yellow). The colored bands indicate the uncertainties due to various models

Irradiation effects on emerging memory systems

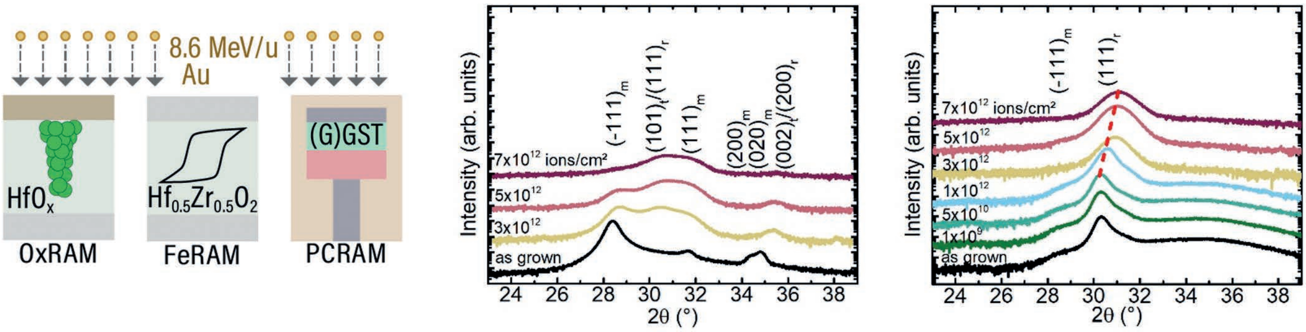

Figure 10. (Left) Schematic representation of different memory types, OxRAM, FeRAM and PCRAM based on HfO_x, $HfZrO_2$ and Ge-rich GeSbTe ((G)GST) irradiated in order to test radiation-induced effects on the switching process. (Center and right graph) X-ray diffraction data of monoclinic HfO_2 (center) exposed to different fluences of 8.6 MeV/u Au ions reveals a transition to the rhombohedral phase, whereas for initially rhombohedral HfO_x (right) films the phase remains stable even under high fluences.

Hafnium oxide (HfOx) and Ge-Sb-Te (GST) based functional layers are promising material candidates for emerging memory technologies for data storage applications. Emerging non-volatile memory types such as oxide-based (OxRAM), ferroelectric (FeRAM), and phase-change random-access memory (PCRAM) are discussed as contenders for flash-based systems for applications in radiation-harsh environments (Figure 10 left). An international collaboration (TU Darmstadt, GSI Materials Research, Fraunhofer IPMS in Dresden and CEA-LETI as well as CNRS-LTM in Grenoble) investigated the effects swift heavy ions induce in various HfO_x-based as well as Ge-rich GST-based systems. The irradiations were performed with 8.6 MeV/u Au ions at the UNILAC up to fluences of $1{\times}10^{13}$ ions/cm². The initial crystallinity, composition and microstructure of the memory materials have a crucial influence on their radiation hardness (cf. Figure 10 center and right) [2]. Testing the switching properties in combination with structural analysis revealed that changes of the crystalline and microscopic structure are directly connected to the memory states and failure mechanisms of the memories. All tested systems were found to withstand ion impacts of at least $5{\times}10^{10}$ Au ions/cm² without obvious damage (Figure 10 right). At fluences above $1{\times}10^{12}$ ions/cm², a phase transition accompanied by grain fragmentation occurred in HfO_x-based stacks, which is ascribed to the creation of oxygen vacancies. In GST-based stacks, changes of the crystallinity were related to beam-induced bond-breaking and bond-(re)creation due to creation of (localized) heat.

Ion-induced desorption of copper samples with different surface and heat treatments for accelerator applications

Ion-induced desorption processes in heavy ion accelerators are a serious limitation for the intensity and lifetime of the beams. To gain a better understanding of how surface conditions and bulk material affect the gas desorption, the number of released molecules per impacting ion (desorption yield) was determined by bombarding oxygen-free copper samples with Ca^{10+} and Au^{26+} ions (4.8 MeV/u) at the M-branch (UNILAC). The surfaces were treated by different combinations of milling, polishing and sputtering. It turned out that thermal annealing at 400 °C for about 4 h under ultra-high vacuum conditions is a most promising method to remove volatile outgassing molecules from deeper layers, thus reducing high-energy ion induced desorption. Surprisingly, annealed samples stored under ambient conditions retain their low desorption yield for at least 9 months (Figure 11 left). Storage in argon reduces the desorption yield even further by a factor of about 3. Reduced desorption was also obtained by polishing or milling the samples, but the effect is less pronounced. In conclusion, we recommend thermal annealing under UHV conditions (400 °C, 4 h) to achieve low-desorbing accelerator components. Ideally, the annealed components should be stored in argon before being mounted.

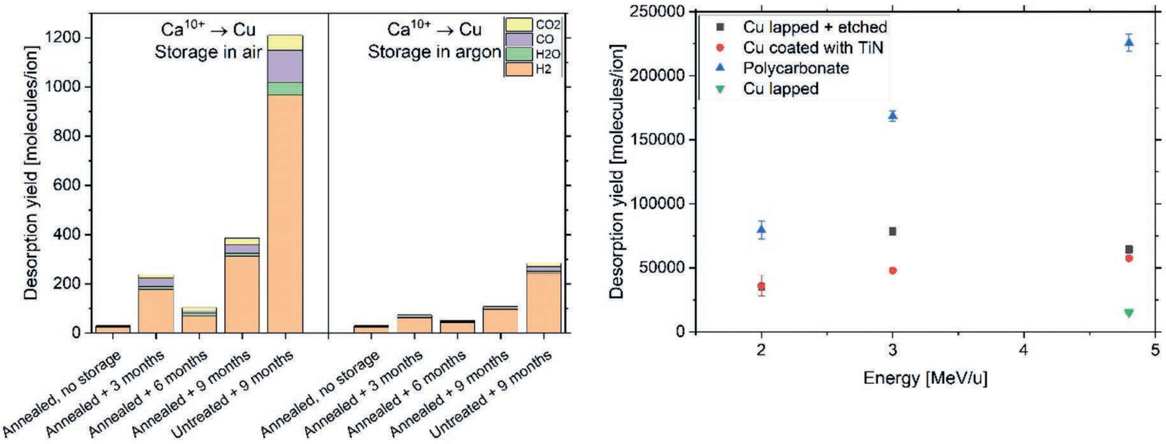

Figure 11. (Left) Desorption yields of H_2, H_2O, CO and CO_2 for milled copper samples annealed for 4 h at 400 °C in ultra-high vacuum with storage in atmosphere or argon. (Right) First results of desorption measurements at CRYRING using hydrogen-like Au^{78+} ions of different energies. Error bars include only statistical errors.

First desorption measurements were also performed at the MAT extraction beamline of the CRYRING using hydrogen-like Au^{78+} ions of energy between 2 and 4.8 MeV/u (Figure 11 right). Such experiments are of interest to better understand the surface interaction processes of ions with such high charge states (high potential energy). Although the CRYRING beam suffers from low intensities, the desorption process under such extreme conditions was high enough to quantify desorption yields for a variety of materials. Improved diagnostics and beam tuning of the accelerator settings is needed to further reduce systematic errors.

Luminescence properties of diamond under swift heavy ion irradiations

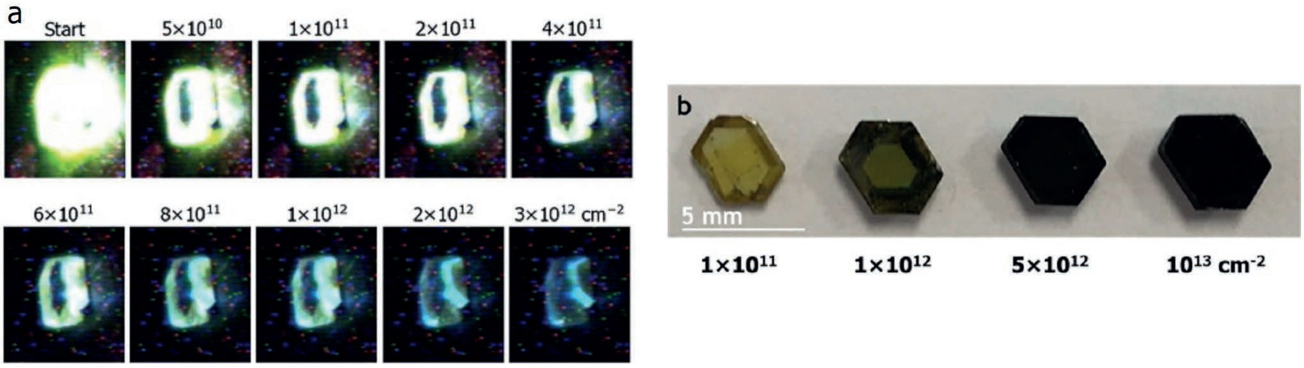

Figure 12. Type Ib diamond samples exposed to different fluences of 4.8 MeV/u Au ions. (Left) Camera observation of ion-beam induced luminescence during irradiation (courtesy of M. Tomut), (right) irradiated samples showing severe color changes.

To test the suitability of diamond as luminescent screens for high-power particle beams, the luminescence properties of type Ib diamonds (200 ppm of substitutional nitrogen), both bulk and crystals embedded in copper and titanium matrices, were investigated under 4.8 MeV/u heavy-ion beams. Samples were observed online by luminescence spectroscopy, insitu infrared and UV/vis absorption spectroscopy and depth-resolved photoluminescence spectroscopy after irradiation. The results show that the luminescence properties change rapidly (Figure 12). The samples lost at least 80% of their initial integrated ionoluminescence intensity after irradiation with 2×10^{11} cm^{-2} 4.8 MeV/u Au ions. The application as a luminescence screen for high-intensity beams is obviously severely limited.

Absorption spectroscopy indicates that the trend is independent of substitutional nitrogen content up to a level of at least 200 ppm, as similar results have been observed in virtually defect-free diamonds synthesized by chemical vapor deposition. In the photoluminescence spectra, several beam-induced defects were identified that exhibit strong sensitivity towards electronic energy loss at vacancy densities below the breakdown of the diamond lattice. As these defects create electronic levels within the diamond bandgap, they also affect the electronic properties. These results are of particular interest for future FAIR experiments whenever diamond detectors are exposed to heavy particles of high electronic energy loss.

Nanochannels filled with metal–organic frameworks as switchable nanofluidic devices

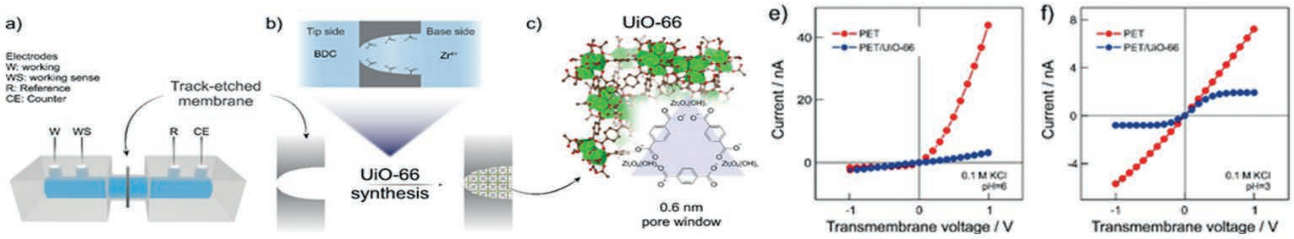

Figure 13. (a) Schematic of the electrochemical cell used for ion current measurements, (b) asymmetric nanochannel filled with (c) UiO-66 metal organic framework, (d) and (e) I-V curves for a bare (red) and a UiO-66 filled (blue) nanochannel in 0.1 M KCl, measured at pH 6 and pH 3, respectively.

Swift heavy ions provided by the UNILAC are used as nanostructuring tool for the fabrication of isoporous polymer etched ion-track membranes. Nanochannels with tailored dimensions allow fine-tuning of ionic transport properties and can be used for (bio)sensing and energy-harvesting applications. Recently, the metal organic framework (MOF) UiO-66 was synthesized inside single track-etched nanochannels by the interfacial growth method (Figure 13). Compared to unfilled nanochannels, the pH-dependent ionic transport of MOF-filled nanochannels exhibits remarkable characteristics including the saturation of ionic current above certain transmembrane voltages, which opens new opportunities for the design of ionic circuits and logical devices [4].

Outlook for 2023

Following the 'Call for Proposals' for beamtime planned 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 2024, FAIR Phase-0 activities will continue at all MAT-operated beamlines. The installation of an in situ confocal UHV-Raman spectrometer is planned at the MAT target station of the CRYRING. The high-pressure irradiation platform will be further developed in terms of control systems and dosimetry. At the M-branch, the in-situ scanning electron microscopy will be upgraded by in situ electrical conductivity measurements. Research activities in the fields of nanotechnology, radiation hardness of materials, and functional materials will be carried on. The department activities in the two cross-center Helmholtz Innovation pool projects, MaDQuanT (Materials Dynamics for Future Quantum Technologies) and FISCOV, as well as in the highly interdisciplinary IVF project CORAERO will be continued. The research objectives of the latter two initiatives deal with the development of porous substrates for protein crystallography and virus sensors for pandemic prevention, respectively.

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2.3 Plasma physics

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The study of high-energy density (HED) plasmas with high pressures (Mbar) and temperatures (eV to keV) is relevant to the understanding of astrophysical objects such as planets and stars, as well as for the interaction of (ultra-) intense laser pulses with matter, or the goal to reach thermonuclear fusion by inertial confinement. Powerful drivers such as large laser facilities and accelerators allow generating such extreme states of matter in the laboratory.

The Plasma Physics department operates various experimental sites at GSI for experiments in the field of HED science. At the Z6 target area in the experimental hall of the UNILAC, a unique combination of ion pulses from the linear accelerator with laser pulses from the high-energy laser facility PHELIX enables precision measurements of ion stopping power in laser-generated hot plasmas. Stand-alone laser experiments can be conducted in the PHELIX laser hall, where relativistic intensities in high-energy picosecond pulses are available for experiments in the area of relativistic laser-matter interaction, laser-particle acceleration, and generation of intense secondary sources. Finally, at the high-temperature experimental station HHT at the output of the SIS18 synchrotron, heavy-ion pulses with $>10^9$ ions per bunch can be focused to millimeter spot-sizes and compressed to sub-µs pulses, allowing to volumetrically heat macroscopic samples to extreme conditions. With the recently completed new high-energy laser beamline from the PHELIX building to the HHT cave, experiments combining this novel path to generate extreme matter states with diagnostic techniques based on laser-driven secondary sources can be conducted.

Within the current FAIR Phase-0, these GSI facilities are also vital for the FAIR-relevant research program of the international FAIR collaboration HED@FAIR, which aims at exploiting the worldwide 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

Like the GSI accelerator complex, the PHELIX laser facility, currently delivering the most energetic laser pulses within Germany, is operated by the department as a user facility, i.e. open to the international scientific community, with beamtime access granted by an external program advisory committee. In 2022, 45% of the time was used for beamtimes and preparation. This is slightly less than in the past years due to the following two reasons: One experiment had to be finished earlier as several members of the experiment crew were diagnosed with Covid-19 in the course of the beamtime. Furthermore, during the setup phase of the last experiment in 2022, a power supply failure in the PHELIX short pulse frontend caused severe damage to this part of the laser. Although the repair of the system could be done in a short time, the experiment had to be shifted to January 2023. The repair took several weeks, leading to an unusually long total maintenance time of 45%. As a result, only six instead of the initially planned seven experiments were conducted with PHELIX in 2022, covering a diverse range of topics including laser ion acceleration, nuclear photonics, relativistic laser-matter interaction, laser-driven pressure waves for material strength testing, and the first experiments using laser-driven x-ray sources to diagnose ion-heated samples.

The evaluation of questionnaires handed out to the users at the end of their beamtime showed good feedback about PHELIX operation. A total of 381 shots on target were recorded in the PHELIX shot database, with a shot success rate of 98.2%. This underlines the high level of reliability of the system in its fifteenth year of user operation. The shifting of an entire experiment by several weeks due to technical failure was unprecedented, and a thorough investigation of the incident and of possible additional risk mitigation strategies is underway.

Besides a strong emphasis on the reliable operation of the laser system, a strong and continued effort by the laser team is devoted to improving quality, in order to retain a competitive edge compared to similar laser facilities and offer laser performance at the highest level to the users. One example is the further development of adaptive optics to reach the highest intensities, using a deformable mirror in conjunction with a following beam diagnostic to reduce wavefront aberrations. Ideally, this should be done after the compression stage of the system in order to avoid transferring wavefront aberrations into spatio-temporal couplings, which cannot be compensated easily. Doing so also requires a wavefront sensor behind the compressor, which should be able to measure the wavefront on-shot in order to verify the successful compensation of aberrations. At PHELIX, we have developed a new, ultra-compact post-compressor beam diagnostic [1], measuring the wavefront over the full aperture of 28 cm. Using leakage light behind the last turning mirror of PHELIX, the beam is demagnified by an off-axis parabola (OAP) telescope in vacuum and attenuated by a Mach-Zehnder Interferometer style beam splitter/shutter combination. The rest of the system consists of a regular in-air attenuator/imaging system and a camera box with beam diagnostics. The alignment can be done using a backpropagating alignment laser in both a double-pass configuration (for the in-air part) and an intermediary focal spot diagnostic in the OAP telescope. In a first commissioning of this system, we were able to demonstrate an increase of the on-shot intensity by a factor of 3 to $1.4 \cdot 10^{21}$ W/cm^2.

In experiments using such ultra-high intensity pulses, a high temporal pulse contrast is mandatory to avoid premature destruction of the target, in particular when irradiating sub-micron-thin samples. Improving the temporal contrast has therefore been a long-standing activity at PHELIX, having enabled laser-acceleration of protons to record-high energies. Already now at PHELIX, the intensity level up to 100 ps before the main pulse, dominated by ASE and unavoidable reflections, is approximately 11 orders of magnitude below the peak intensity. However, intensities above the ionization threshold are reached some 10’s of picoseconds before arrival of the main pulse due to a rising intensity ramp that is most likely due to spatio-spectral coupling in the stretcher, a feature found at virtually all Petawatt-class CPA laser systems worldwide. In 2022, a beamtime dedicated to studying the temporal contrast degradation originating from the pulse stretcher could experimentally confirm that a significant contribution to temporal contrast degradations comes indeed from the stretcher predominantly. The beamtime also showed that other contrast degradation sources exist in the system, that still remain to be investigated.

While the upgrade project of the new laser beamline delivering high-energy laser pulses to the HHT-station had already been completed and the beamline successfully commissioned in 2021, this year further testing and optimization allowed to ramp up the beamline to the full specified pulse energy of 200 J. These energetic laser pulses allow to produce hot laser-driven plasmas, used as intense pulsed x-ray sources for diagnostic backlighting of samples heated by the heavy-ion beam.

Highlights in 2022

The Laser Ion Generation, Handling and Transport (LIGHT) beamline at Z6 is part of the ATHENA distributed facility, where phase-space manipulations of laser-generated ion beams is the main emphasis. In the last two years, the LIGHT collaboration focused on the study of the ion-stopping power of plasmas, a key process in inertial confinement fusion for understanding energy deposition in dense plasmas. The most challenging regime is found when $v_{\text{projectile}} \approx v_{\text{thermal,e,}}$ a regime for which ion stopping is difficult to describe and the existing theories show high discrepancies. To meet this goal, our recent studies have dealt with ions of lower kinetic energies. In 2021, laser accelerated carbon ions were transported with two solenoids and focused temporally with LIGHT’s radio frequency cavity. A pulse length of 1.2 ns (FWHM) at an energy of 0.6 MeV/u was achieved. In June 2022, protons with an energy of 0.6 MeV/u were transported and temporally compressed to a pulse length of 0.8 ns. A stopping power experiment in cold matter was conducted successfully. The stopping power experiment with a plasma target is planned for 2023. The plasma will be generated by the nanosecond laser system nhelix, which is currently being upgraded to deliver the required energies.

Neutrons constitute an important probe for non-destructive material investigation. Complementary to x-ray and gamma radiation, the neutron interaction cross-section is material and isotope sensitive and appreciable even for low-Z materials, however, the availability of sufficiently intense neutron sources is limited to large facilities such as reactors or accelerator driven spallation sources. At PHELIX, laser-accelerated intense bunches of protons and deuterons have been used to produce neutrons via (p,n) and (d,n) reactions in a low-Z converter. Use of a specially designed moderator results in an epithermal spectrum. With this laser-driven neutron source, neutron radiography could be successfully demonstrated. Exploiting the short pulse duration, isotope sensitive detection via energy resolved measurements further allowed the demonstration of neutron resonance imaging, and resonance spectroscopy, the latter being shown to detect even sub-percent impurities [3]. These techniques have a large potential for important societal applications, and are also being considered as diagnostic probes for HED matter samples.

Within the framework of the ATHENA project that establishes a distributed plasma accelerator facility between various Helmholtz centers, GSI has developed a common high-temporal-contrast laser module to be implemented by the ATHENA partners at their facility. In 2022, the system planned for the PEnELOPE laser at HZDR has been built, characterized and delivered. A similar system is also in operation at PHELIX, where feedback on operation already exist. Having similar systems within Helmholtz greatly reduces operation cost via cost and resources sharing.

In 2022, the plasma physics department coordinated a research grant application within the Horizon Europe program of the European Commission. The 10,5 M€ THRILL project was successfully evaluated and it will start in 2023, with GSI as coordinator, to work on technology bottlenecks for high-energy high repetition rate lasers with partners in France, Czech Republic, Germany and Belgium.

FAIR Phase-0: Experiments at the HHT-cave

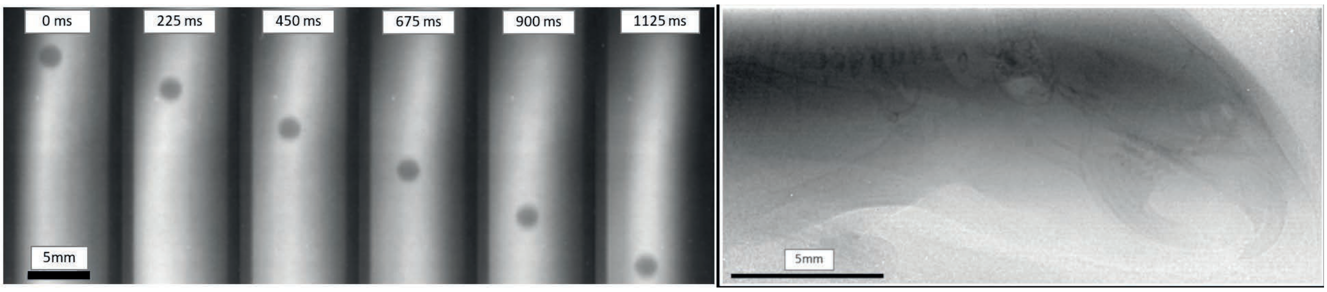

Figure 14. (left) A tungsten-carbide ball falling through molten sulfur inside a heated pressure vessel at a temperature of T=650K and a pressure of 1300PSI. (right) A mouse specimen imaged with 4.5GeV protons from the SIS18 during the 2022 PRIOR-II experimental campaign.

Exploiting the exceptional beam parameters expected from the SIS100 synchrotron for research in HED science, a number of schemes have been proposed. Some of these schemes can already be explored, at lower intensities, at the HHT-cave with ion bunches from the existing SIS18. These activities in the FAIR Phase-0 are crucial to prepare, test and optimize the experimental setups, to commission and calibrate detectors, and to assess and mitigate possible background issues. The two schemes that are currently most actively being fielded are the proton microscope PRIOR, and the heavy-ion heating scheme HIHEX.

Following the successful commissioning of the new PRIOR-II proton microscope – a powerful diagnostics facility for high energy density states of matter with an unprecedented spatial, temporal and density resolution performance – the first semi-dynamic experiment with PRIOR-II was fielded during the 2022 run cycle using 2.5 GeV protons from the SIS18 synchrotron. The experiment S488 developed by Prof. Bjoern Winkler at the Goethe University in Frankfurt aims at the accurate determination of the viscosity and densities of molten matter at high temperatures and pressures, which is experimentally very challenging. Such data is needed to understand terrestrial magmatism or complex processes such as the formation of channels on the surface of Venus stretching over several thousands of kilometers. Thanks to the excellent penetration depth of SIS18 high-energy protons through thick and dense matter, the PRIOR-II proton microscope allows for the observation of such processes within pressure vessels with very high spatial and temporal resolution.

For this particular experiment, a heated pressure vessel setup was developed that allows for a determination of density and viscosity of sulfur at the conditions found, e.g., on the surface of Venus. PRIOR-II was able to provide an accurate density reconstruction of the samples investigated and – for the first time at the HHT experimental area – captured high-speed proton image sequences of the dynamic target using slow extracted proton beams with a total duration of up to two seconds (see Figure 14).

As part of the collaboration with the Los Alamos National Laboratory, the PRIOR team and US guest scientists have also evaluated the performance and suitability of several new scintillator detector materials for use with high energy and high-speed proton radiography. This is a vital development for future investigations of shock-compressed matter at extreme densities at GSI and FAIR, a process that happens on the ns-scale. Fundamental physics in shock-compression experiments probing the density regimes that are also relevant for inertial confinement fusion are currently being prepared and planned to be fielded during the next years at GSI, where PRIOR-II will serve as a unique diagnostic tool for this field of research.

Further investigations have been carried out with animal specimen proving the outstanding sensitivity of high-energy protons up to 4.5 GeV in low-density samples (Figure 14, right). While several limitations of this technique may prevent a future application in clinical scenarios, the accuracy and data acquisition speed make it very suitable for in-vivo imaging applications in FLASH cancer therapy research. A small and relatively compact setup could be deployed at any low energy proton facility and used for accurate online position and treatment verification for small animal experiments.

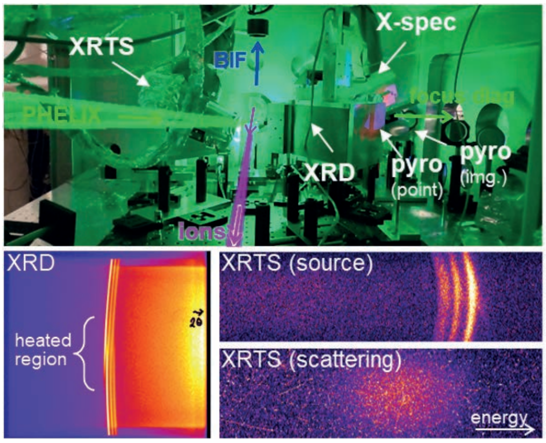

Figure 15. (top) Experimental setup inside the APPA-target chamber, installed at the HHT-cave, and (bottom) examples of x-ray diffraction and x-ray Thomson scattering signals from heavy-ion heated samples.

An important milestone has been achieved in 2022, with the first beamtime at the HHT-area combining both intense pulses of heavy-ions from SIS18 and high-energy laser pulses (S489). In this experimental campaign, carried out in collaboration with various institutions from within the HED@FAIR collaboration, we have successfully demonstrated the feasibility of such combined experiments and showed that our x-ray diagnostics are capable of revealing microscopic properties of HED samples generated by the heavy-ion beam. In a pump-probe setup, the ion bunches are used to volumetrically heat solid density samples, while the laser pulses generate a hot plasma to provide an intense pulsed x-ray source (see Figure 15). Focusing up to 200 J of laser energy (wavelength 527 nm, pulse duration 2 ns) to intensities of order 10^{15} W/cm^2, we have achieved conversion efficiencies of up to 0.1% into He-alpha line radiation (4.5 keV for Ti, 5.9 keV for Co). We have used this x-ray radiation to perform x-ray diffraction, revealing the microscopic structure of the driven samples. In addition, we have used spectrally resolved x-ray Thomson scattering as a sensitive microscopic measurement of the ion temperature. These x-ray probing schemes are vital and routinely used diagnostic techniques at HED-facilities worldwide, and are thus an essential capability for HED research at FAIR. Importantly, this very first combined laser-ion beamtime has provided valuable insight into the background from ion-induced secondary radiation, and allowed us to successfully test mitigation and shielding concepts. Furthermore, as a crucial input for heavy-ion heating schemes, we have explored novel methods of in-focus measurements of the ion fluence distribution, and have tested two newly developed optical pyrometry setups for temperature measurements based on thermal emission.

Outlook for 2023

In 2023, the plasma physics group will continue supporting FAIR and the HED@FAIR collaboration by holding various workshops with the community and pushing enabling technologies and diagnostics for FAIR experiments, exploiting the opportunities of FAIR phase-0.

One step in this direction, supported by the third-party project THRILL, is the establishment of a blue print for a high-energy laser coupled to the APPA cave. Such capability, which has been on the Helmholtz roadmap of infrastructure, adds the versatility in pump-probe experimental setups at the APPA cave that makes full use of FAIR unique ion beam properties for HED science.

Selected publications of 2022

- [1] Ohland, J. B. ; Eisenbarth, U. ; Zielbauer, B. ; et al:Ultra-compact post-compressor on-shot wavefront measurement for beam correction at PHELIX. High power laser science and engineering 10, e18 (2022), DOI:10.1017/hpl.2022.9; Ohland, J. B. ; Zobus, Y. ; Eisenbarth, U. ; et al: Alignment procedure for off-axis-parabolic telescopes in the context of high-intensity laser beam transport. Optics express 29(21), 34378 (2021), DOI:10.1364/OE.439658
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- [3] Zimmer, M. ; Scheuren, S. ; Kleinschmidt, A. ; et al: Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source. Nature Communications 13(1), 1173 (2022), DOI:10.1038/s41467-022-28756-0

2.4 Biophysics

Head: Prof. Dr. Marco Durante, Technische Universität Darmstadt & GSI
Author: Marco Durante

The Biophysics Department studies the biological and medical applications of high-energy heavy ions, with two main applications: cancer therapy and space radiation protection. It is a highly interdisciplinary department, with nearly 100 members with background in physics, biology, chemistry, and engineering. The Department is organized now in 9 groups, with a new one created in 2022 (Space Radiation Biology) and directed by Dr. Charlot Vandevoorde, previously director of the radiobiology group at iThemba National Laboratory in South Africa. With the release of the pandemics rule, it became possible to host the 2nd edition of the ESA-FAIR Summer School with 16 students from all over the world studying and working on space radiation protection at ESOC and GSI in Darmstadt.

International Biophysics Collaboration at FAIR

The Biophysics Department is part of the APPA pillar at FAIR. The International Biophysics Collaboration (IBC) is a large network of accelerator facilities in operation or under construction with scientific programs in biomedical applications. In 2022, IBC had beamtime in April (heavy ions for space research) and May (carbon ions for therapy-related research). IBC implemented 8 experiments selected by ESA within the AO-IBER-19 proposal, 3 on radiation hardness selected within the ESA-IRES contract, and 13 selected by the Bio-PAC in 2020. More than 50% of these experiments were performed by IBC groups external to the GSI Biophysics Department. The Bio-PAC meeting in 2022 was very selective because only 23 shifts could be assigned out of 80.4 shifts requested by the IBC. This resulted in only 10 experiments being granted an “A” plus other 6 ranked “A-“, i.e. possibly implemented only if beamtime will become available. The large number of applications shows, however, the high interest of IBC for FAIR Phase-0. Additional 20 shifts have been granted by the ESA-PAC in the framework of the IBER contract for space radiation research experiments.

Awards

Several members of the Biophysics Department received awards in 2022. Dr. Timo Steinsberger got the Christoph-Schmelzer Award 2022 for the best doctoral thesis. Martina Quartieri won the best poster award at the 47th Annual Meeting of the European Radiation Research Society (ERRS). The paper "Compensating for beam modulation due to microscopic lung heterogeneities in carbon ion therapy treatment planning" by Paz et al. received the prestigious Farrington Daniels Award of the American Association of Physicists in Medicine (AAPM) for the best paper published in the official AAPM journal, Medical Physics, in 2021. Finally, during the 60th Annual Meeting in Miami (June 2022), Prof. Dr. Marco Durante was elected President of the Particle Therapy Co-Operative Group (PTCOG), the association of all particle therapy centers worldwide. It is the first time that the PTCOG president comes from a German institute, and the first time that this position is given to a researcher rather than a clinician. The mandate of the President is 3 years and can be renewed once.

Highlights in 2022

This year was exceptionally productive for the Biophysics Department, with 50 peer-reviewed papers in the repository. A few highlights are provided below.

FLASH

Ultra-high-dose rate radiotherapy (FLASH) is the new frontier of cancer therapy [1]. A few years ago, in fact, a French-Swiss collaboration has shown that exposure of animals to very high intensities (>40 Gy/s) strongly reduces normal tissue toxicity whilst maintaining tumour control. These high intensity cannot be achieved with X-rays, but have been measured with electrons (from linacs) and protons (accelerated in cyclotrons). In the frame of FAIR Phase-0 we have used the SIS18 synchrotron at GSI in 2022 in FLASH regime, using a single 5×10^9 C-ions synchrotron spill, corresponding to about 100 Gy/s in a 20x20 mm^2 target. We have optimized the online dosimetry in FLASH conditions using special optimised He/CO_2 gas mixtures, for minimising recombination and maximising the possible voltage [2]. With this setup (Figure 16), we were able to demonstrate that ultra-high dose rate C-ion beams can control the tumour, but have reduced toxicity in the muscle tissue [3]. Interestingly, the osteosarcoma model we used creates numerous lung metastasis in the mouse. Irradiation with C-ions of the hind limb tumors reduces lung metastasis, but this reduction is significantly higher when FLASH conditions are used [3]. These results are very important as they could potentially expand the advantages of FLASH irradiation in clinical settings.

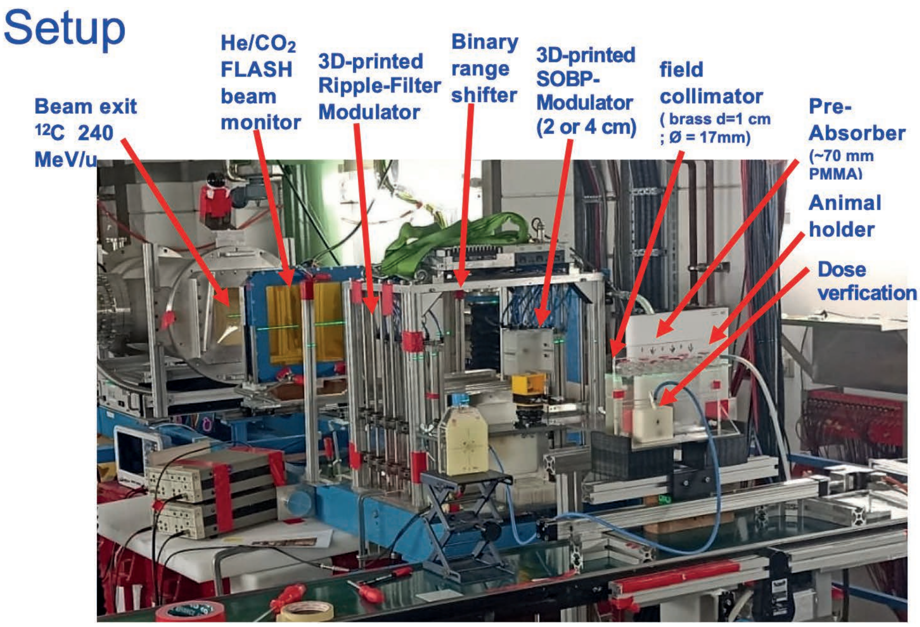

Figure 16. Experimental setup in Cave A for FLASH radiotherapy tests with heavy ions. Photo by Dr. Uli Weber, reproduced under CC-BY 3.0 license.

BARB

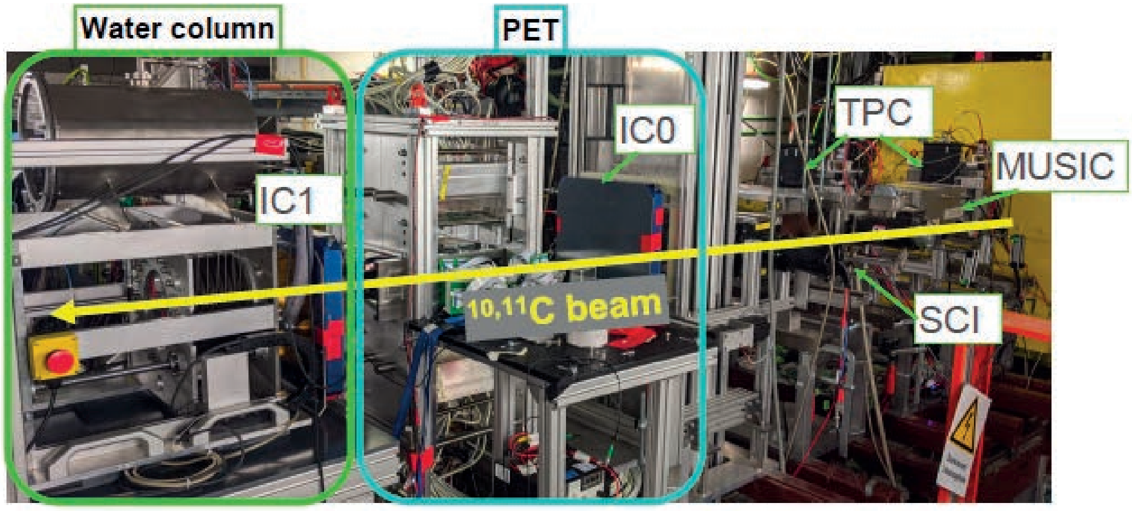

Figure 17. Experimental setup located at the final focal plan of the FRS. IC=ionization chambers; TPC=time projection chamber; MUSIC= Multi-Sampling Ionization Chamber; SCI= scintillator. Image by Dr. Daria Boscolo, reproduced under CC-BY 3.0 license.

The ERC Advanced Grant “Biomedical Application of Radioactive ion Beams” (BARB) was awarded to Marco Durante in 2020. BARB is an inter-pillar FAIR experiment, a strong collaboration between APPA (Biophysics Department) and NuSTAR (FRS). The first results of the dosimetry and physical characterization of the beam have been published this year (Figure 17) [4]. In addition, we studied the potential impact of radioactive ion beams in patients with an in silico approach. The idea was to show which toxicity reduction is expected by reducing the irradiated margins around the tumour. We have demonstrated that a significant reduction of the normal tissue complications for both serial (e.g. optical nerves) and parallel (e.g. liver) organs when margins are reduced (Figure 18) [5]. The Bio-PAC granted the beamtime that in 2024-25 will eventually lead to the key experiments to demonstrate the potential benefit of radioactive ion beams in cancer therapy.

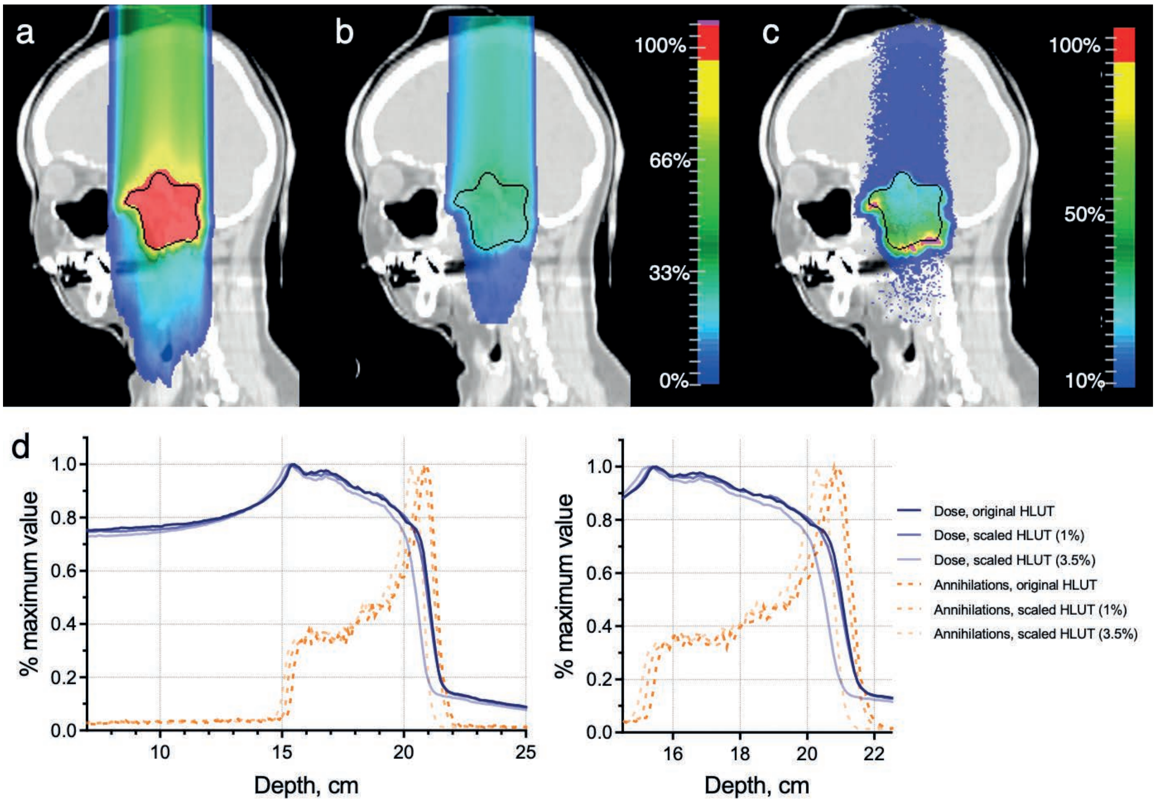

Figure 18. Dose and activity distributions calculated in a head-and-neck cancer patient to be treated with radioactive ^{11}C ions. (a) RBE-weighted dose map calculated with TRiP98 treatment planning software, (b) absorbed dose and (c) annihilation maps calculated with FLUKA for a single-field ^{11}C treatment plan optimized in a patient CT. Color bars reflect the respective distributions with red corresponding to the maximum observed values. (d) Normalized beam-eye-view profiles extracted from the dose and annihilation maps for the original treatment plan and those optimized using the scaled Hounsfield look-up tables (for 3.5% or 1%) to mimic the range uncertainties. Depth is given in the CT coordinates. Blue solid lines: dose profiles, orange dashed lines – annihilation profiles. Left plot is a zoom-in of the distributions in the target region. Figure reproduced from reference [5], open access under CC-BY 3.0 license.

Outlook for 2023

There will be no beamtime at GSI on 2023 so the year will be dedicated to publish the results obtained during the 2022 FAIR Phase-0 run and to perform selected experiments in other accelerators (HIT, Marburg and CNAO). It will also be important to plan carefully the 2024 beamtime, which includes many new experiments selected by the Bio- and ESA-PAC as well as new contracts. For instance, we have to plan the new experiments funded in the European program HEARTS about space radiation protection and the decisive proof-of-principle *in vivo* experiment in BARB. In July we will also host the 3rd edition of the ESA-FAIR Summer School.

Selected publications of 2022

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- [2] Baack, L. ; Schuy, C. ; Brons, S. ; et al: Reduction of recombination effects in large plane parallel beam monitors for FLASH radiotherapy with scanned ion beams. Physica medica 104, 136 - 144 (2022), DOI:10.1016/j.ejmp.2022.10.029
- [3] Tinganelli, W. ; Weber, U. ; Puspitasari, A. ; et al: FLASH with carbon ions: Tumor control, normal tissue sparing, and distal metastasis in a mouse osteosarcoma model. Radiotherapy and oncology 175, 185 - 190 (2022), DOI:10.1016/j.radonc.2022.05.003
- [4] Boscolo, D. ; Kostyleva, D. ; Schuy, C. ; et al: Depth dose measurements in water for 11C and 10C beams with therapy relevant energies. Nuclear instruments & methods in physics research / A 1043, 167464 (2022), DOI:10.1016/j.nima.2022.167464
- [5] Sokol, O. ; Cella, L. ; Boscolo, D. ; et al: Potential benefits of using radioactive ion beams for range margin reduction in carbon ion therapy. Scientific reports 12(1), 21792 (2022), DOI:10.1038/s41598-022-26290-z

3. Research of the Compressed Baryonic and Quark Matter Departments

Coordination: Prof. Dr. Joachim Stroth (Goethe-Universität Frankfurt, GSI & Helmholtz Research Academy Hesse for FAIR)

The three departments ALICE, CBM and HADES are dedicated to the study of QCD matter under extreme conditions. While the ALICE experiment operates with ion and proton beams in the TeV center-of-mass energy range and studies the properties of QCD matter with high energy density, a state of matter similar to the universe about 10 μs after the Big Bang, the HADES and CBM experiments explore matter at the highest net-baryon densities that can be produced in heavy-ion collisions in laboratory experiments at SIS18 and SIS100. The latter studies are complemented by experiments addressing various hadron physics aspects like meson-baryon couplings and the structure of baryon resonances using proton and pion beams with HADES.

The ALICE department acts as German host for heavy-ion physics activities at CERN and takes major responsibilities in the operation of the ALICE detectors (foremost in the TPC) and in various management and coordination positions. This happens in tight cooperation with the German university groups organized within the ErUM Pro Topical Research Program ALICE. The activities in 2022 were driven by the start of LHC Run-3 in summer 2022 with a number of detector upgrades accomplished and a smooth ramp-up, the past year has also seen important physics results using data taken in Run-2.

The CBM department was deeply involved in the preparation for mass production of the central silicon strip tracking detector stations, where in particular the impact had to be mitigated due to the exclusion of groups affiliated to institutions located on the territory of the Russian Federation. A great achievement has been the successful operation of the mCBM set-up with beam and the reconstruction of the first Lambda signal using a single-arm setup and the full chain of data acquisition based on freely streaming detector information.

The HADES collaboration started the year with a proton beam campaign of four weeks duration. The experiment was conducted jointly with the HADES-PANDA collaboration and employed new detector systems based on PANDA straw technology, Low-gain Avalanche Diodes and Single-cell RPCs as well as a scintillator-based detector system with APD read-out. A total of 35 billion events were recorded representing a luminosity of about 5 pb^{-1}. Among the research highlights are the measurement of the N*(1520) Dalitz decay and lifetime measurements of light hypernuclei.

The activities of the CBM and HADES department are carried out in close collaboration with the German University groups organized in the ErUM Pro Topical Research Program C.B.M.).

3.1 ALICE at GSI

Head: Prof. Dr. Silvia Masciocchi (Universität Heidelberg & GSI), Dr. Ralf Averbeck (GSI)
Authors: Andrea Dubla (GSI)

The aim of the ALICE Collaboration is to study the physics of strongly interacting matter at the highest energy densities reached so far in laboratories colliding heavy ions. In such collisions, an extreme phase of matter - called the quark-gluon plasma (QGP) - is formed. Our universe is thought to have been in such a primordial state for the first few millionths of a second after the Big Bang before quarks and gluons were bound together to form protons and neutrons. As the universe expanded, the QGP cooled. When the temperature dropped to roughly a hundred thousand times that of the core of the Sun, hadrons formed. Recreating this primordial state of matter in the laboratory and understanding how it evolves will allow us to shed light on questions about how matter is organized and the mechanisms that confine quarks and gluons.

The ALICE department at GSI has been playing a leading role since many years in most aspects of the ALICE Collaboration. Major responsibilities regarding the operation, calibration, maintenance, and upgrade of the Time Projection Chamber (TPC), which is the heart of the ALICE tracking and particle-identification system, rest with members of the ALICE group and the GSI detector laboratory. Key contributions were also given to the processing of ALICE data from previous years, from reconstruction to data analysis with various physics topics in mind. Furthermore, GSI group members hold leading positions in the scientific coordination and in the management of the experiment.

Commissioning and operation of the upgraded Time Projection Chamber

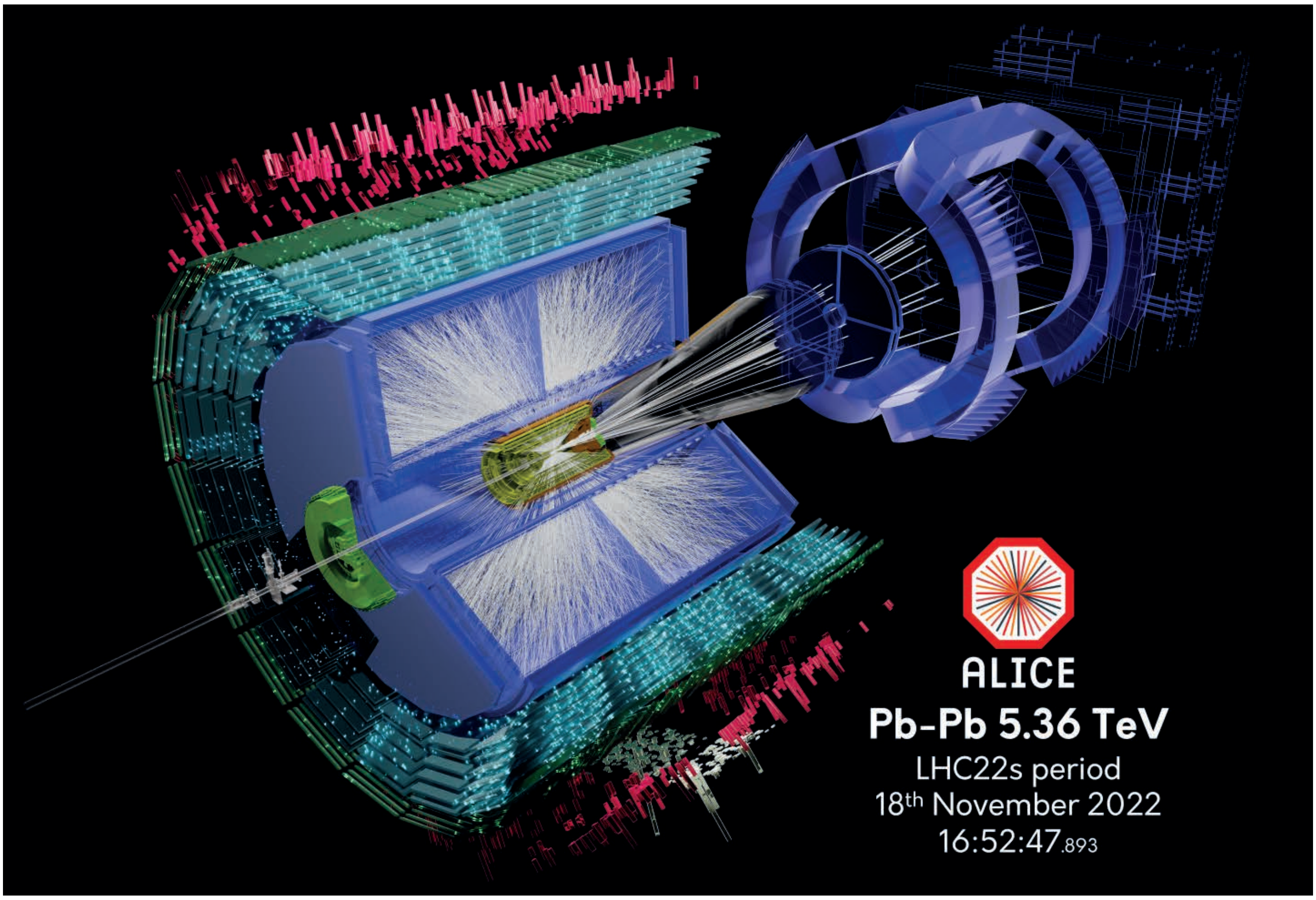


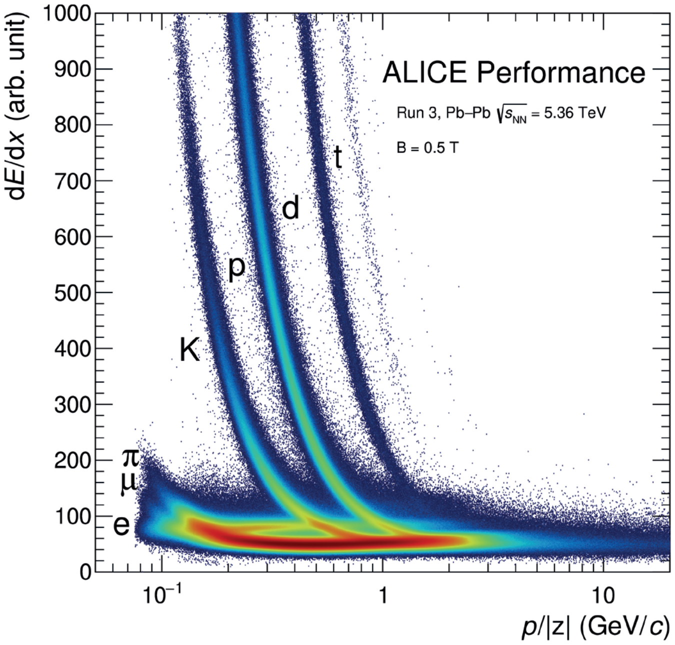
Figure 19. Event display of the first LHC Run 3 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV on November 18th, 2022.

The ALICE group at GSI takes a central role in the commissioning and operation of the upgraded TPC, and, in a joint effort with the scientific computing department, in the realization of the new Online-Offline facility and software framework (the O2 project). The ALICE TPC has undergone a major upgrade in recent years. The readout chambers (of which a large part was assembled at GSI in the previous years) and electronics have been exchanged, in order to cope with the requirements defined by the task to read out all lead-lead (Pb-Pb) collisions at an interaction rate of 50 kHz, improving the rates previously attainable by a factor of about 100. The multiwire proportional chambers were replaced by chambers equipped with four Gas Electron Multiplier foils each to allow for continuous readout while keeping the ion backflow below 1%, minimizing space-charge effects from amplification ions entering the drift volume. Nevertheless, significant space-point distortions due to space charge are expected at the highest interaction rates in Pb-Pb collisions. In addition, space-charge density fluctuations lead to distortion fluctuations which have to be corrected on time scales of 10 ms in order to preserve the intrinsic tracking resolution of the TPC. While the average space-charge distortions can be corrected using information from external detectors as a reference, data-driven machine learning algorithms and convolutional neural networks are in development, under the coordination of scientists in the ALICE GSI group, to provide the correction for the distortion fluctuations. The correction of the average space-charge distortions and the distortion fluctuations is performed in multiple steps during both synchronous and asynchronous reconstruction, aiming to restore the intrinsic track resolution and particle-identification capabilities of the TPC after the final calibration.

An extensive commissioning program for the TPC was performed and recently completed. It included measurements of laser tracks and cosmic particles, as well as the irradiation of the TPC with an intense X-ray source and the flushing of the chamber with radioactive Krypton to carry out a pad-by-pad gain calibration. The commissioning of the upgraded ALICE experiment culminated in 2021 in one week with “pilot beams”, which included proton-proton (pp) collisions at 900 GeV. During the first proton-proton collisions in Run 3 the TPC performed according to specification.

A new period of operation with proton-proton (pp) collisions started on the 5th of July 2022 for the ALICE experiment at the Large Hadron Collider (LHC) at CERN, after more than three years of upgrade and maintenance work. The ALICE experiment has been systematically ramping up the interaction rates, with the goal of running with up to 50 kHz in Pb-Pb collisions. In order to achieve this goal, a new data processing scheme and software are developed. Calibration of the detector response in such running conditions is a challenging task for understanding and processing the data. For this, the GSI team developed the advanced software tools “Skimmed data” and “RootInteractive framework” for a reliable and fast-turnaround optimization of the calibration and reconstruction algorithms.

On the 18th of November 2022, a test run with Pb-Pb collisions was carried out in the LHC and provided an opportunity for the ALICE experiment to validate the new detectors and new data-processing systems ahead of the Pb-Pb physics run in 2023. In this test, lead nuclei were accelerated and collided at a record energy of 5.36 TeV per nucleon pair. Figure 19 shows an event display of the first LHC Run 3 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV.



ALI-PERF-529714

Figure 20. Specific energy loss (dE/dx) in the TPC as a function of particle rigidity. Results are shown from the analysis of Pb-Pb collisions recorded in November 2022 at $\sqrt{s_{NN}}$ = 5.36 TeV.

This was an important milestone in preparation for the physics runs with lead-lead collisions that are planned for 2023 and the following years of Run 3 and Run 4. The new detector was demonstrated to provide a high spatial resolution in the reconstruction of the trajectories and properties of the particles produced in the collisions. In addition, with the upgraded apparatus and processing chain ALICE managed to record the full collision information at a rate two orders of magnitude higher than in previous years. ALICE researchers verified that the readout and signal handling also worked as expected. An additional major challenge is the enormous amount of data generated during heavy-ion collisions - for the TPC alone, the data volume is several terabytes per second. To sufficiently reduce the amount of data stored, the data stream must be processed in real-time using effective pattern recognition methods. The success of the upgrade, commissioning, operation, and calibration of the TPC is demonstrated by the high-quality specific energy loss (dE/dx) as a function of particle rigidity, reported in Figure 20, as measured with the TPC in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV.

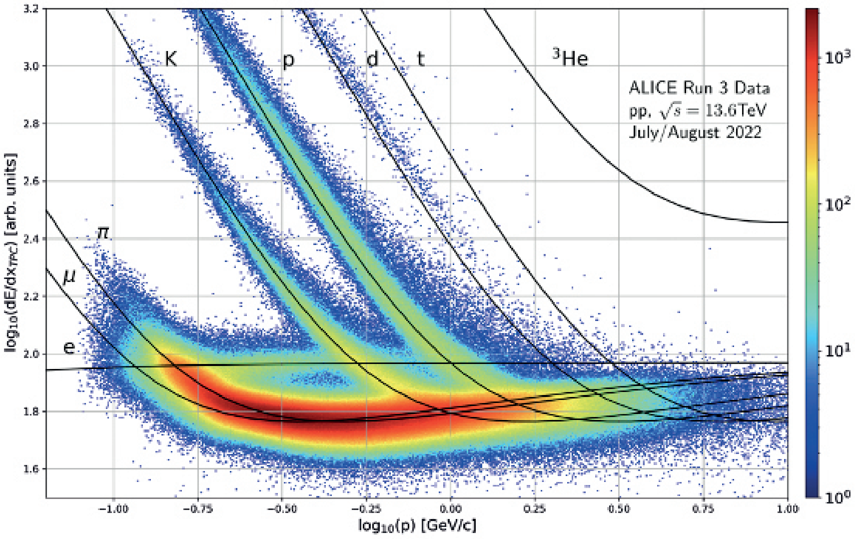


Figure 21. Specific energy loss as a function of particle momentum in pp collisions. Several particle species can be separated from each other based on their parameterized Bethe-Bloch curves.

Concerning particle identification with the TPC, a new tool based on neural network regression is in development within the GSI team. Starting with the initial ALEPH parameterization of the Bethe-Bloch formula shown in Figure 21, a novel method for the determination the Bethe-Bloch initial parameters based on hyperparameter optimization with the OPTUNA libraries, which does not rely on initially assigned particle identities, has been developed. With the usage of neural network regression, the new framework is capable of finding corrections to the parametrization of the mean energy loss per unit distance given by the theoretical prediction of the Bethe-Bloch formula, which will bring particle identification with the TPC to a new level of precision.

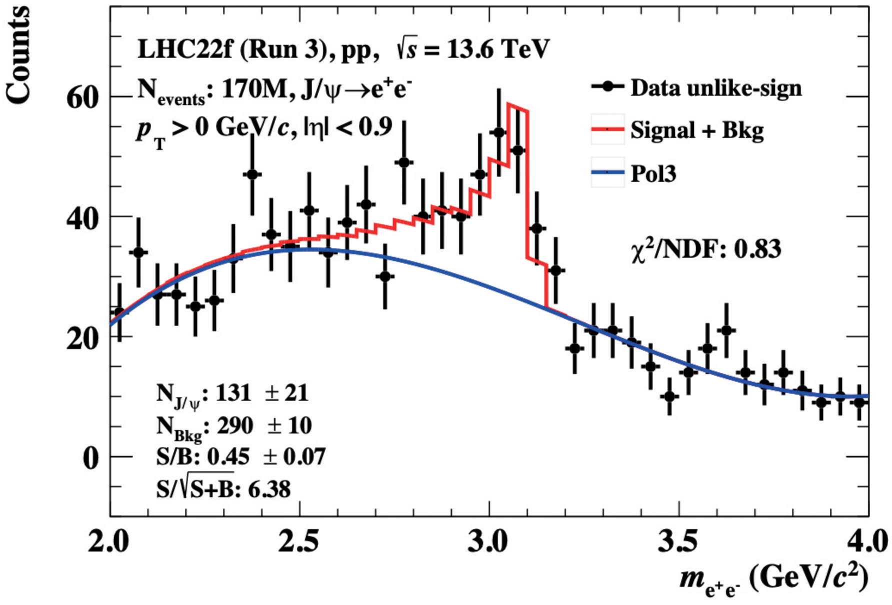


Figure 22. Invariant-mass distribution of electron-positron pairs at midrapidity in pp collisions at √s = 13.6 TeV.

Meanwhile, the physics analysis groups are completing the harvest of results from the Run 2 data, which were recorded until 2018. Continuing the strong track record of the GSI group, new results on open heavy-flavor hadron and J/Ψ-meson production, as well as particle correlations with respect to the spectator plane were obtained. The total number of ALICE publications has reached the number of 418, of which 49 were completed in 2022. Most recently, the analysis of Run 3 data has also started. Despite the not-yet-final calibration of the detector, the first J/Ψ meson signal has been reconstructed by GSI scientists as illustrated in Figure 22. Using the Kalman-Filter package, J/Ψ meson candidates have been reconstructed from only 170 million events out of the 80 billion collected in 2022.

3.2 CBM at FAIR

Head: Prof. Hans Rudolf Schmidt (GSI & Univ.Tübingen)
Authors: Kshitij Agarwal (University of Tübingen), David Emschermann (GSI),
Norbert Herrmann (University of Heidelberg), Johann Heuser (GSI), Christian Sturm (GSI)

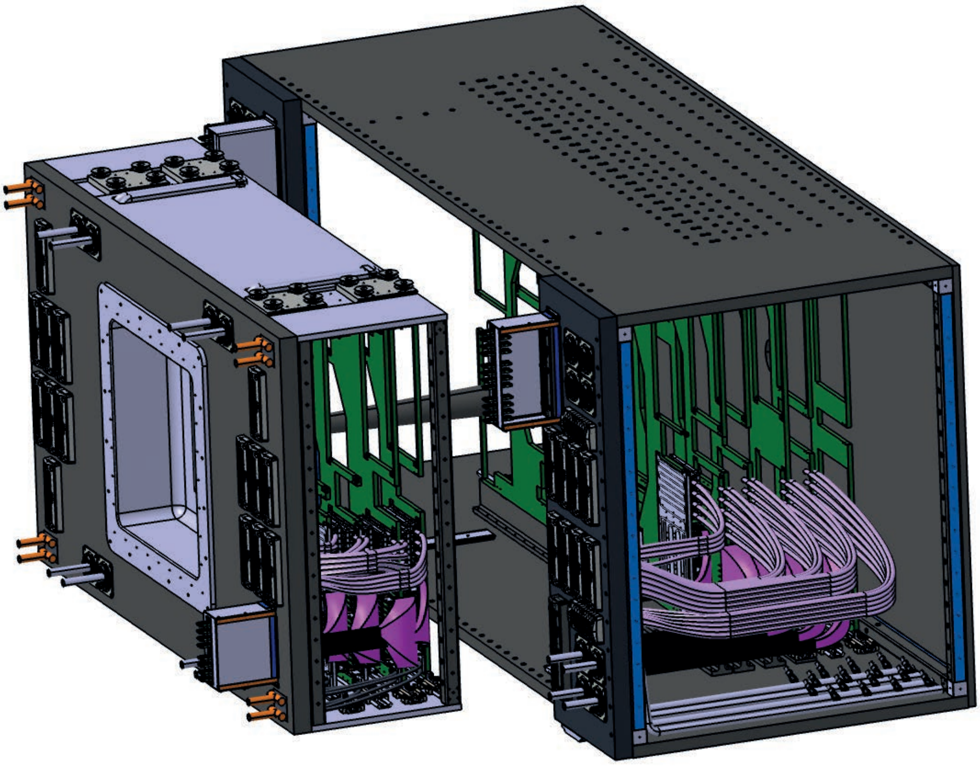


Figure 23. STS setup showing the two sections housing 3 layers (front) and 5 layers (back) of tracking stations, respectively.

In 2022, CBM had to deal with the consequences of the war in Ukraine. This means that the delivery of the dipole magnet of the Budker Institute in Novosibirsk is cancelled. JINR Dubna is also no longer available as a cooperation partner. Dubna would have been responsible for the production of about 40% of the modules of the silicon tracker. The project timeline, though, should remain essentially unchanged, with the beginning of component series production by mid 2023, and detector ready for installation into the CBM cave at the end of 2026. This puts high workload on the remaining two assembly centers GSI and KIT; compensation for missing workforce is to be found.

A major activity concerned a change to the STS mechanical design. With CBM's dipole magnet not being available as in-kind contribution from Russia anymore, the search for a new provider offered also the opportunity to revisit design specifications – and to optimize the STS detector residing in its gap. A slightly higher and wider magnet gap can accommodate a mechanically modified STS system, now made of two assembly blocks of tracking stations instead of one, while leaving its internal components unchanged (Figure 23). The two upstream and downstream building blocks can be assembled individually before joining them into one system in the integration laboratory. This may facilitate a possible upgrade in the future, while leaving the detector's physics performance for CBM's day 1 configuration essentially unchanged.

Highlights & Activities in 2022

CBM's Role in Inferring Neutron Star Properties

Understanding the nature of strongly interacting matter at supra-saturation densities (> $n_{sat} = 0.16$ fm^{-3}), in terms of the underlying nuclear Equation of State (EOS) has been one of the outstanding problems, both for nuclear physics experiments and astrophysical observatories, over the past decades. The role of CBM experiment at SIS100 in this multi-messenger effort was further substantiated by an effort published in [1] where Bayesian inference was used to combine existing EOS information from the heavy-ion experiments based at SIS18 and astrophysical observations of neutron star radii and their mergers (cf. Figure 24). A remarkable consistency between these two sources of information was observed, in terms of pressure inside a neutron star, at densities reached at SIS18 energies (around 1.5 n_{sat}). At the same time, neutron star properties at higher densities (around and above 2.5 n_{sat}) are driven by the astrophysical observations because of lack of reliable information from heavy-ion experiments. CBM-FAIR will be able to probe these higher densities in gold-gold collisions ($\sqrt{s_{NN}}$=2.9-4.9 GeV) and provide pivotal information to infer properties of dense nuclear matter properties in controlled laboratory conditions. Moreover, CBM's importance in global nuclear physics community was further highlighted in proposals for the US Nuclear Physics Long-Range Plan [2,3]. The latest progress in CBM's physics performance simulations, the underlying detector sub-systems and FAIR Phase-0 activities are reported in [4].

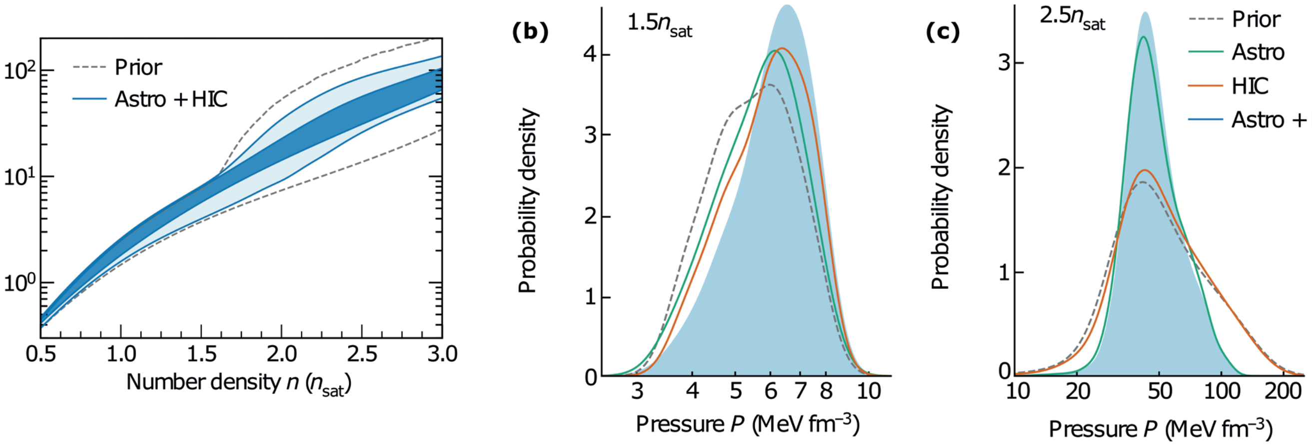


Figure 24. (a) Neutron Star Equation of State (EOS), in terms pressure and number density, after combined Bayesian analysis of nuclear theory ("Prior") and combined astrophysical observations and heavy-ion collisions ("Astro + HIC"). (b) Probability density function at 1.5 n_{sat}. (c) Probability density function at 2.5 n_{sat}. Figure adapted from [1].

FAIR Phase-0: Achievements of the mCBM experiment

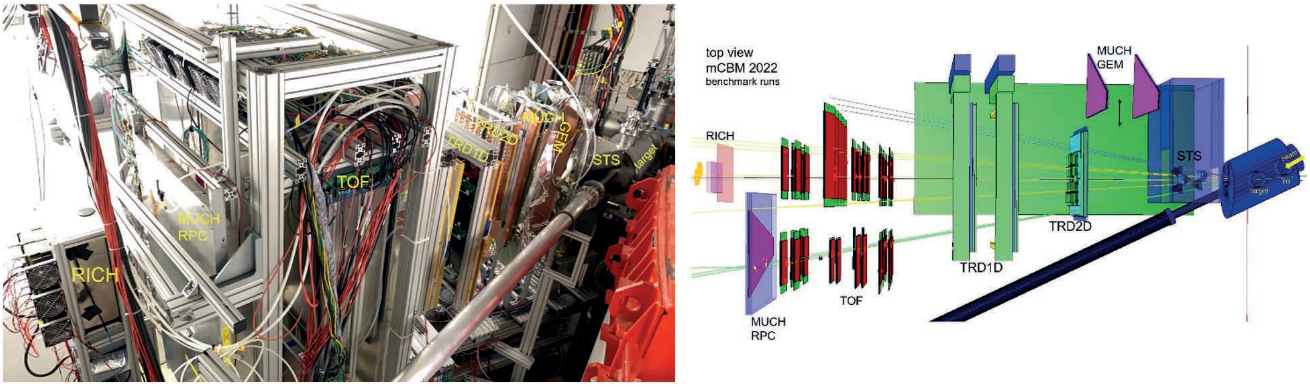


Figure 25. Photograph (left side) and Geant geometry (right side) of the mCBM experiment in 2022, the beam enters from the right. The following CBM detector subsystems are installed in the mCBM experiment: the fast and segmented diamond counter for time-zero (T0, part of BMON) determination positioned 20 cm upstream of the target, the Silicon Tracking System (STS) subsystem equipped with 11 modules in 2 stations, the Muon Chamber (MUCH) subsystem, which consists of 2 GEM modules and 1 RPC module mounted downstream of the TOF detector, the Transition Radiation Detector (TRD) subsystem, comprising of one detector module for the inner TRD region (TRD2D) complemented with two large detector modules for the outer TRD region (TRD1D), the Time-of-Flight (TOF) subsystem with RPC modules grouped into two stacks and the Ring Imaging Cherenkov (RICH) subsystem using two aerogel radiators placed directly behind the TOF detector delivers a second measurement of the particle velocity in a selected acceptance window.

The CBM full-system test-setup named mCBM@SIS18 (short "mCBM") was set up 2017 and 2018 at the GSI experimental area Cave D (HTD) of the SIS18 facility of GSI/FAIR. The primary aim of the mCBM experiment is to test prototypes or pre-series productions of the CBM detector systems and to commission and optimize the complete data chain developed for the CBM experiment. In particular, it allows testing of the free-streaming read-out electronics and data transport to a compute cluster as well as the online reconstruction and selection under realistic experiment conditions up to the top CBM interaction rates of 10 MHz. To further validate the read-out and data processing concept of CBM the production yield of Λ baryons is studied in nucleus-nucleus collisions serving as a benchmark observable, which will allow comparison with published data by the FOPI and HADES experiments. The Λ baryon carries strangeness and hence, is a rare probe at SIS18 energies due its high production threshold.

The mCBM experiment is taking SIS18 beam since 2019 within the FAIR Phase-0 program. After years of development the final CBM configuration of the DAQ and data transport system could be realized in 2021 integrating a FPGA based Common Readout Interface (CRI) and a first version of a Timing and Fast Control System (TFC). The system was successfully tested in O+Ni collisions at 2.0AGeV kinetic projectile energy, running at approx. 1 MHz collision rate in July 2021. First benchmark runs were measured in May and June 2022 taking $5 \cdot 10^9$ Ni+Ni collisions at 1.93AGeV and $2 \cdot 10^{10}$ Au+Au collisions at 1.23AGeV kinetic projectile energy.

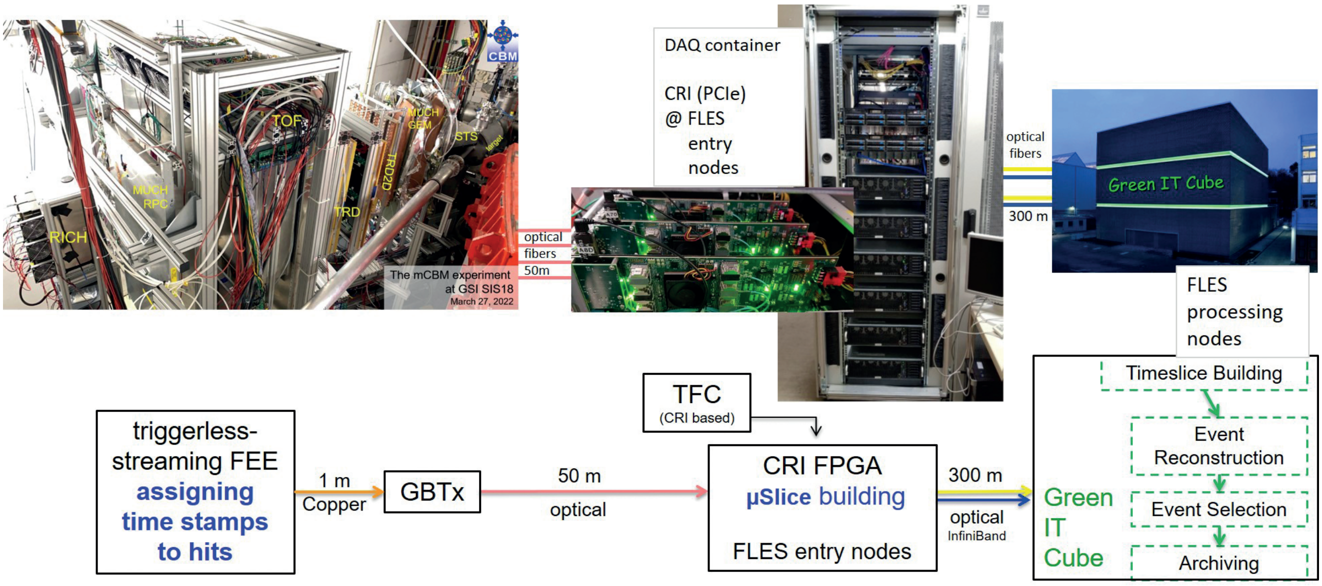


Figure 26. Sketch of the free-streaming (triggerless) CBM DAQ and data transport system already in use at the mCBM experiment (along the data path): front-end ASICs at the detector stations inside the experimental area Cave D assign time-stamps to the raw hit massages. The time synchronization is provided by the Timing and Fast Control (TFC) system. The data are forwarded via a copper connection to the CERN GBTx readout board where the electrical signals acquired through a large number of e-links are converted and merged into an optical GBT link (link speed of 4.48 Gbit/s). The GBT links interface the detector subsystems with the PCIe-based Common Readout Interface (CRI) boards integrated in the First Level Event Selector (FLES) entry nodes, located inside the mCBM DAQ container. The present CRI version (v1.0, "BNL-712 v2") has been developed by the Brookhaven National Laboratory (BNL) and is based on the XILINX Kintex UltraScale FPGA. Timeslice building, online event reconstruction and selection is performed by the FLES proessing nodes of a compute cluster inside the Green IT Cube of GSI/FAIR.

As depicted in Figure 25, the mCBM experiment is positioned downstream a solid target under a polar angle of about 25° with respect to the primary beam towards a beam dump located 7 m downstream at the south end of the experimental area. Due to the limited space inside the experimental area, mCBM does not comprise a magnetic field, and, therefore, measures charged particles produced in nucleus-nucleus collisions traversing the detector stations under straight trajectories. The mCBM setup includes prototype or pre-series detector stations of the CBM detector systems T0 (BMON), STS, MUCH, TRD, TOF and RICH as shown in Figure 25. To cope with extremely high collision rates up to 10 MHz the CBM DAQ and data transport has been developed as a free-streaming (triggerless) system, which is already in use at the mCBM experiment, sketched in Figure 26. As detector front-end chips ultra-fast and radiation-tolerant ASICs are deployed digitizing signals above threshold and assigning time stamps to the raw hit messages. By means of a Timing and Fast Control (TFC) system, the detector front-ends are time-synchronized to the nanosecond level. Via the CERN GBTx based data aggregation unit the data streams are transported to the entry nodes of the First Level Event Selector (FLES). Here, FPGA-based PCIe boards are integrated in the FLES entry nodes serving as a Common Readout Interface (CRI). The FLES processing nodes mounted in the Green IT Cube of GSI/FAIR conduct a final time-slice building containing the time-sorted raw data messages of all detector systems. On this base, a parallelized event reconstruction and selection will be performed on the FLES compute cluster. A first data scan confirms a high data quality with stable synchronization. The benchmark runs show that the readout system performs reliably over long periods.

As a first step of the data processing, the raw hit messages packed and compressed in TimeSliceArchive (tsa) files are being unpacked and converted into C++ objects called CbmDigis by applying individual subsystem time-offset corrections as well as involving the detector channel mapping and first calibration steps. After data unpacking, a first, simplified event building is performed based on a time-cluster search within a time window defined by the timing response of a reference detector system. Identified event candidates are selected based on Digi-multiplicities of selected detector stations or its combinations and stored as CbmDigiEvents in ROOT files for further analysis steps. For the following, event candidates are accepted including at least one Digi-hit in the T0 diamond counter (TOF start) and at least four Digi-hits in different TOF detector modules.

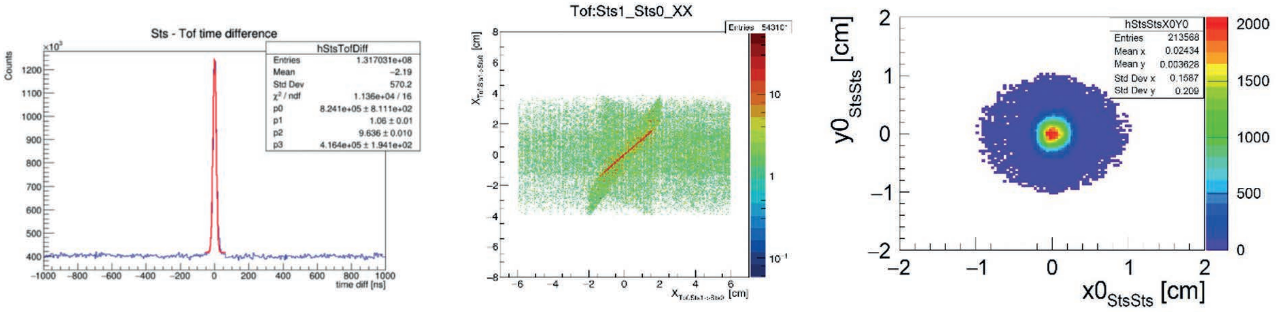


Figure 27. The stable synchronization is exemplarily shown by the measured (digi) time differences STS – TOF within a given time window (left figure); correlation between spatial coordinates of both STS stations with TOF modules based on tracks (middle) and reconstructed vertex (right figure).

As a key requirement of a free-streaming readout system, the CRI branches of all detector subsystems were stably synchronized. A stable timing of the front-end electronics of all detector subsystems was observed within the expected time resolution, demonstrated exemplarily for the STS detector system in the left panel of Figure 27. All time differences are displayed within the given time window measured by the STS detector subsystem with respect to the time of the TOF system. Individual time offsets of the detector subsystems were corrected during the unpacking stage; no detailed time calibration procedures were applied. The subsystem time offsets remain constant during runs as well as between runs. Supplementary to the correlation in time (Figure 27, left), correlations of spatial coordinates are presented in Figure 27 (middle), exemplary between both STS stations and TOF modules. The displayed correlations are based on tracks formed from reconstructed detector hits in both STS stations as well as including hits of the TOF wall. The resulting vertex reconstruction is shown in Figure 27, right panel. The dimension of the reconstructed vertex matches reasonably with the beam spot measured on the scintillation target of the beam diagnostics station, upstream in front of the mCBM target chamber.

Detailed high-rate studies were performed in 2021 and 2022 using various beams with collision rates up to 10 MHz, benefiting substantially from the highest available beam intensities at GSI SIS18. Accordingly, rate scans were conducted investigating the rate capability of the CBM detector systems including their readout, in particular for the TOF RPC detector modules as well as for the MUCH GEM and RPC detectors. Furthermore, MIMOSIS-I sensors for the CBM Micro Vertex Detector (MVD), LGAD sensors for the CBM beam monitor system and front-end ASICs (STS-XYTER v2.2) for the STS system were exposed with charged particle fluxes at or even beyond their design limits to study the bit-flip and latch-up probability. First results indicate a high radiation tolerance of the exposed sensors and chips. While the data analysis of the rate scans is ongoing, a sufficient stability of the readout system has been proven to achieve 40 ps timing resolution of the TOF RPC modules. At the highest counting rates of about 25 kHz cm^{-2} the observed TOF time resolution reduces to the measured 70 ps for the system and 52 ps for single RPC counters at a slight efficiency degradation, well in line with the requirements on the CBM TOF system.

The assignment of a particle mass to the track candidate is based on the decay topology of the Λ decay into a proton p and a negatively charged pion π- as shown in Figure 28 (left panel). Due to its mass the proton carries most of the Λ momentum and is being therefore emitted mainly in the direction of the decaying Λ while the much lighter pion is stronger deflected. Hence, the pion track projected to the target features a larger distance to the primary vertex in the target plane and therefore is being distinguished to a proton track by its larger distance-of-closest approach (DCA). Additionally, the measured velocity is required to fall into a predefined proton or pion range which was determined by Monte Carlo – simulations of Λ decays. Pairs are formed from proton and pion candidates applying further selection criteria like on pair DCA or on the opening angle between the proton and pion candidate. The preliminary invariant mass distribution M_{inv} of the so-selected proton-pion pairs is shown in the right panel of Figure 28, observed in Ni+Ni collisions at 1.93 AGeV kinetic projectile energy. All selected pairs are displayed in blue color (Same event) and the combinatorial background in cyan color (Mixed events). The combinatorial background was determined by pair combinations of protons and pions which stem from different events (mixed events) to exclude correlations. Even without background subtraction a clear Λ signal with a signal-to-background ratio (S/B) of about 22 is observed. After background subtraction (Same - Mixed, green distribution) a Gauss fit (red curve) results to a signal yield of 334 at a mean invariant mass of about 1.115 GeV. The signal yield amounts to an integrated probability of $6 \cdot 10^{-7}$ in the selected event sample. The raw data sample of 8.1 TB (tsa files, run 2391) was taken at an average collision rate of about 400 kHz on May 26th, 2022, in a total run time of about 2 h.

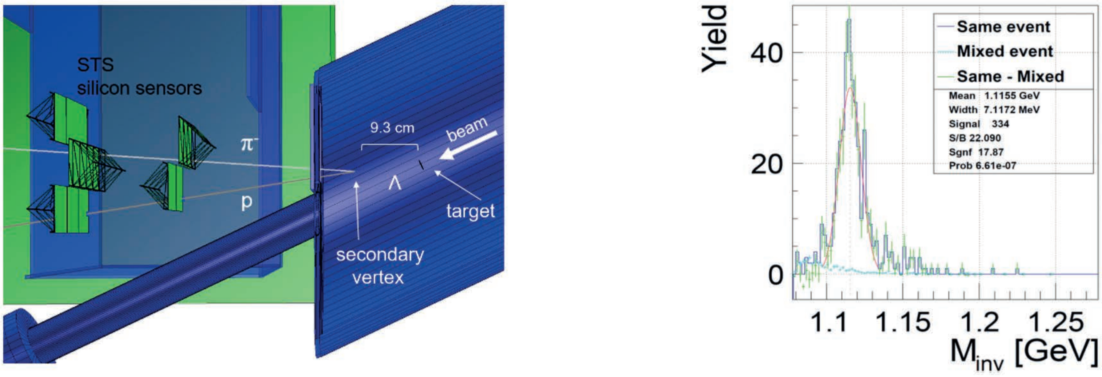


Figure 28. Left panel: A Monte-Carlo simulation of a single Λ decay is shown within the corresponding GEANT geometry of mCBM; Right panel: preliminary invariant mass distribution M_{inv} of pairs formed from proton and pion candidates in Ni+Ni collisions at 1.93 AGeV kinetic projectile energy: all selected pairs in blue color (Same event), the combinatorial background in cyan color (Mixed events) and in green color after background subtraction (Same – Mixed).

The identification of Λ baryons with mCBM demonstrate the feasibility to reconstruct rare signals with the CBM detector systems involving the full CBM data chain. Detailed Monte-Carlo simulations are in preparation determining the acceptance and reconstruction efficiency to convert the observed Λ yield into a production probability for minimum-bias collisions. Furthermore, 180 TB raw data (tsa) files were taken in June 2022 for Au+Au collisions at 1.23 AGeV kinetic projectile energy. The lower projectile energy reduces the Λ production probability significantly (sub-threshold production) while the track reconstruction and selection has to cope with increased ambiguities with respect to the Ni system. Hence, the much more challenging signal-to-background ratio requires a further fine-tuning in terms of the calibration, alignment, track reconstruction and selection criteria. Although a first version of a simplified online selection based on the unpacked, time-offset corrected subsystem data was tested during the 2022 beam campaign raw data were completely archived. Based on the 2022 data the online selection algorithms are further developed and optimized towards the upcoming beam campaign 2023 - 2025.

Outlook for 2023

In 2023, module series production will start. To be ready, CBM-STS has to pass production readiness reviews. An important step in this direction is the pre-series construction of 10 module with all final or most recent prototype components, which has been achieved at GSI. The full chain of steps, from sensor selection based on quality-control data, chip testing, chip-cable assembly, over bonding to sensor and front-end board integration, and the in-assembly testing to final module characterization, was practiced in a row, allowing to assess and improve various details under realistic conditions. The modules have been specifically tailored for installation in the E16 experiment at J-PARC. Together with our associated collaborators at KEK, we look forward to gaining insight into the system performance, and eventually its application to the physics program.

Selected publications

- [1] Huth, S. ; Pang, P. T. H. ; Tews, I. ; et al: Constraining neutron-star matter with microscopic and macroscopic collisions. Nature <London> 606(7913), 276 - 280 (2022), DOI:10.1038/s41586-022-04750-w
- [2] Almaalol, D. ; Hippert, M. ; Noronha-Hostler, J. ; et al.: QCD Phase Structure and Interactions at High Baryon Density: Continuation of BES Physics Program with CBM at FAIR. arXiv (2022), DOI:10.48550/ARXIV.2209.05009
- [3] Sorensen, A. ; Agarwal, K. ; Brown, K. W. ; et al.: Dense Nuclear Matter Equation of State from Heavy-Ion Collisions. INT-PUB-23-001; LA-UR-23-20514; LLNL-TR-844629; arXiv:2301.13253
- [4] Agarwal, K.: Status of the Compressed Baryonic Matter (CBM) Experiment at FAIR. Acta physica Polonica / B / Proceedings supplement 16(1), 1 - (2023), DOI:10.5506/APhysPolBSupp.16.1-A142

3.3 HADES

Head: Prof. Dr. Joachim Stroth (Goethe-Universität Frankfurt, GSI & Helmholtz Research Academy Hesse for Hesse)
Authors: Tetyana Galatyuk (TU Darmstadt, GSI), Anar Rustamov (GSI),
Joachim Stroth (GU Frankfurt,GSI, HFHF)

The HADES department serves as the host of the international HADES collaboration. Members of the department, together with colleagues from Experiment Electronics department assume responsibility for various subsystems of the HADES detector and provide the Technical Coordinator, the Run Coordinator and the Software Coordinator for the HADES Collaboration. Together with the University groups of TU Darmstadt and Goethe University Frankfurt, the department focused its analysis activities in 2022 on the data for the heavy-ion collision system Ag+Ag at a beam energy of 1.58 A GeV and 1.23 A GeV recorded in 2019. Owing to high statistics, remarkable progress has been achieved in the investigation of strangeness production including lifetime measurements for hypernuclei and the observation of Lambda polarization [1]. Another publication focuses on Coulomb effects on the phase space distribution of pions emitted in heavy-ion collisions [2]. Measurement of the dilepton decay of the baryon resonance N*(1520) in pion proton reactions evidencing vector meson dominance in the baryon sector is another highlight (see below). A further achievement is the implementation of the Identity Method, allowing for alternative approach to event-by-event fluctuation measurements, which will also be of importance in preparing respective analysis strategies for the CBM experiment. An innovative approach was developed to account for fluctuations of participant nucleons from event-to-event, which is essential for analysis of fluctuation signals, both in HADES and CBM [5].

A major activity has been the successful conduction of a four-week long experiment investigating the p+p collisions at maximum kinetic energy available from SIS18 of 4.5 GeV. This experiment has been proposed together with the HADES-PANDA collaboration and focuses on the structure of excited hyperon states. For that, new detector system has been installed to complement the HADES spectrometer. It employs PANDA straw tube technology b enabling tracking of charged particles in the very forward hemisphere. In addition, a new forward RPC-based hodoscope is used to provide momentum measurement, and a segmented scintillator array covering the first drift-chamber plane to enhance the trigger purity.

In 2022 we enjoyed common research activities with a total of 7 visiting students from China, France, Poland and Ukraine, and the collaboration with the visiting Humboldt Fellow Maria Stefaniak.

The proton on proton run with new forward detection system (S518)

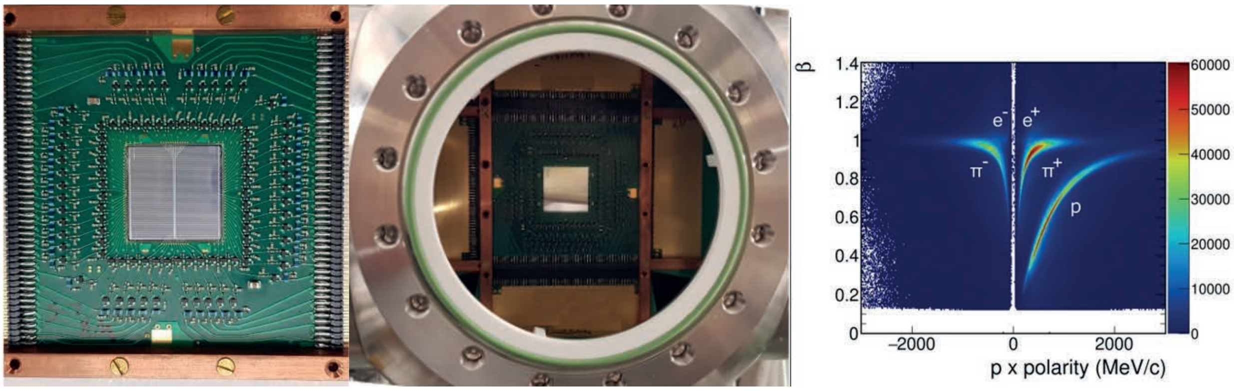


Figure 29. (Left panel) photo of the LGAD sensor integrated on the frontend PCB. A sensor is 2×2 cm^2 large and features two columns of strips with dimension 9.82×0.39 mm^2. The detector is operated inside the beam pipe under vacuum conditions (middle panel). Particle identification by correlation of momentum and velocity measurement in the HADES spectrometer with stop time from an RPC detector array.

During February 2 to March 8 a total of 38 billion events for p+p collisions at a beam kinetic energy of 4.5 GeV were recorded, the biggest data set ever taken by the collaboration. This statistic corresponds to an integrated luminosity of 5.78 pb^{-1} (prel.). It falls about 40% short of the goal ste in the S518 proposal which can mostly be traced back to the micro-spill structure and a beam halo inducing reactions in massive material in the vicinity of the liquid hydrogen target. The newly installed Straw Tracker System (STS), based on PANDA straw technology, and the forward RPC [3], based on R&D conducted for detectors to be used by the R3B Collaboration, worked at the design performance. Another novelty of the experiment was the use of a time-zero detector and beam position monitor based on Low-Gain Avalanche Diodes developed in cooperation with the Bruno Kessler Foundation, Trento, and MedAustron, Vienna [4]. The detector, which consist of two planar sensors of thickness and was exposed to a proton beam with average intensity of 10^8 s^{-1}, 50% of which impinging on an area of 5 mm^2. It represents a non-ionizing dose of ≈2×10^{13} per day. While the high intensity led to a partial deterioration of the performance, an average time precision of σ_{t0}=98 ps could be obtained after a careful calibration including a walk correction. Figure 29 shows from left to right the LGAD sensor, the detector assembly and the PID performance in in combination with the HADES spectrometer. This technology is also prepared for other technologies, as outlined in a sperate chapter later in this section.

Vector Meson Dominance in dilepton decays of baryon resonances

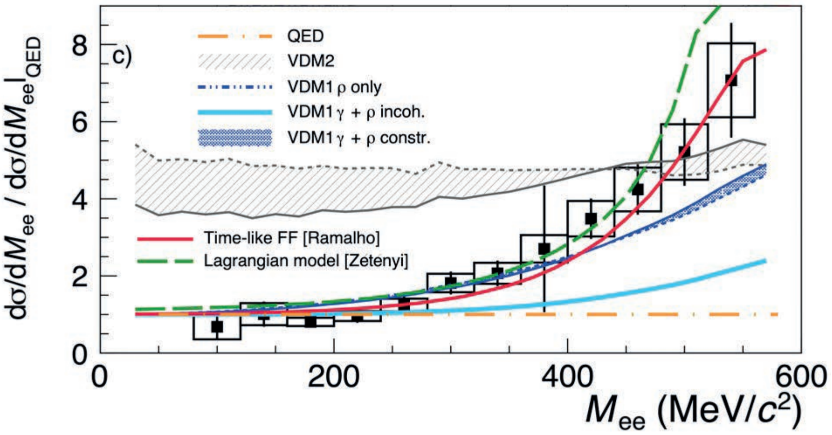


Figure 30. Ratio of the observed exclusive dilepton yield observed in the reaction π^- p->n e^+ e^- at √s=1.49 GeV divided by the expectation assuming a pure QED process. The result is compared to various model calculations using strict Vector Dominance VDM1 and VDM2, and also results from calculations within the timelike Form-Factor model (red solid curve) and the Lagrangian model (green long dashed curve).

The highlight obtained from the pion beam run in 2014 is the first measurement of the electromagnetic transition form factor of the baryon resonance N*(1520). This measurement has been accomplished by combining data from two-pion (π^- p->n π^+ π^-) and dilepton (π^- p->n e^+ e^-) final states. The two-pion data, taken for an energy scan around the second resonance region, where used together with a data set from different exclusive results from other experiments to decompose the reaction cross section in partial waves. This allowed to produce a cocktail of calculations for different models of the radiative decay into the dilepton final state. The dilepton data was taken for √s=1.49 GeV, i.e. for a center of mass energy in the vicinity of the N*(1520) pole mass. The measurement was conducted using a polyethylene target, the signal for the exclusive channel was extracted by missing mass technique and by subtracting the contribution from reactions in the carbon. The latter contribution has been obtained in a separate run using a carbon target. Figure 2 shows the invariant mass distribution for electron pairs in the exclusive channel divided by the QED expectation. The observed rise of the distribution can be interpreted as being related to the formation of virtual rho mesons in the resonance's meson cloud to which the virtual photon couples. This interpretation is supported by model calculations shown in Figure 30 as full red and dashed green lines.

Femtoscopy using the Ag+Ag data taken in 2019

The femtoscopic correlation function A(k*), with k* denoting the relative momentum in the pair rest frame, has been constructed for pairs formed from protons and various light nuclei originating from the same event. Correlations are extracted by comparing the respective distributions to those obtained from truly uncorrelated pairs. The distribution B(k*) is constructed by pairs of reconstructed particles from different events (event mixing) chosen out of sample all belonging to the same centrality class. The correlation function is then constructed as C(k*) = A(k*) / B(k*). The distribution C(k*) is commonly modelled assuming emission from a source characterized by a gaussian source function times a correlation function encoding the Final State Interaction (FSI) between the two particles [1].

Focus of this analysis is on correlations between proton–deuteron (p-d), proton–triton (p-t), and proton–helium-3 (p-3He). The status of the analysis is presented in Figure 31. In case of p-d, the significant negative correlation originates from both, SI and coulomb interaction. The contribution of SI is illustrated by the theoretical prediction calculated with the CorAl software package [2], where SI can be turned on and off. The positive contributions to the

CF of p-d and p-3He originates from the decaying bound states: ^{4}Li -> p + ^{3}He, and ^{4}He* -> p + t (right panel Figure 31). The comparison of these two correlated systems is interesting, as masses of t and ^{3}He are similar and the difference is in the number of protons vs neutrons in the cluster's composition.

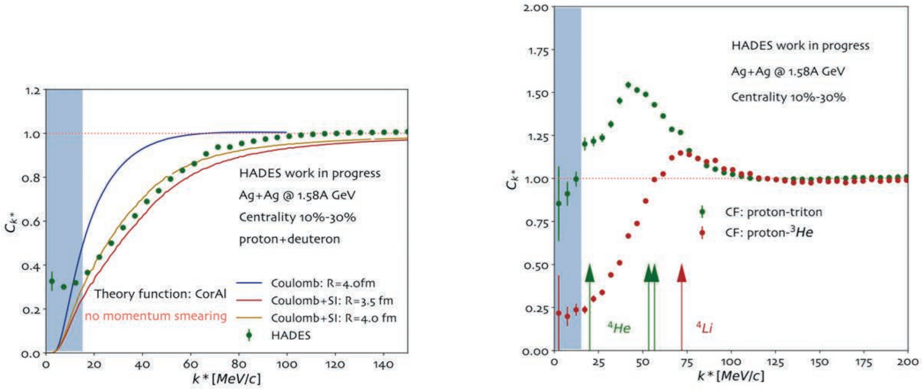


Figure 31. (Left panel) proton-deuteron correlation function: markers correspond to the HADES experimental data points, while curves to theoretical calculations assuming a Gaussian source with radius parameter R. (right panel) Proton-triton (green markers) and proton-helium-3 correlation functions. The green and red arrows correspond to the ^{4}He and ^{4}Li decay energies. In both panels only statistical uncertainties are shown.

Outlook to 2023

Data analysis of the Ag+Ag run is far advanced and a number of publications are in preparation. We expect to present in 2023 new results on the dilepton continuum radiation, strangeness production including hypernuclei lifetime measurements, flow, two- and multi-particle correlations and fluctuation measurements. The analysis of the 2022 p+p run is progressing and the second generation of event reconstruction with advanced calibration and alignment parameters has been produced. Besides data analysis, focus will be on preparing for the next experiment run scheduled for 2024. The HADES detector system is rearranged to the heavy-ion setup and will be available with all six sectors of electromagnetic calorimeter in place. We are also anticipating the installation of the new MDC front-end electronics to the two inner tracking planes.

Selected publications of 2022

- [1] Abou Yassine, R. ; Adamczewski-Musch, J. ; Asal, C. ; et al.: Measurement of global polarization of Λ hyperons in few-GeV heavy-ion collisions. Physics letters / B 835, 137506 (2022), DOI:10.1016/j.physletb.2022.137506
- [2] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al.: Impact of the Coulomb field on charged-pion spectra in few-GeV heavy-ion collisions. The European physical journal / A 58(9), 166 (2022), DOI:10.1140/epja/s10050-022-00796-6
- [3] Blanco, A. ; Fonte, P. ; Lopes, L. ; et al.: The new HADES ToF Forward Detector. Nuclear instruments & methods in physics research / A 1050, 168182 (2023), DOI:10.1016/j.nima.2023.168182
- [4] Krüger, W. ; Bergauer, T. ; Galatyuk, T. ; et al.: LGAD technology for HADES, accelerator and medical applications. Nuclear instruments & methods in physics research / A 1039, 167046 (2022), DOI:10.1016/j.nima.2022.167046
- [5] Rustamov, A. ; Stroth, J. ; Holzmann, R.: A model-free procedure to correct for volume fluctuations in E-by-E analyses of particle multiplicities. arXiv arXiv (2022), DOI:10.48550/ARXIV.2211.14849

4. Research of the NUSTAR Departments

Coordination: Prof. Dr. Christoph Scheidenberger (GSI & Justus-Liebig-Universität Gießen)
Authors: Christoph Scheidenberger and Alexander Herlert

The NUSTAR (Nuclear Structure, Nuclear Astrophysics, Reactions and Superheavy Element research) Collaboration is one of the four major collaborations of FAIR. The NUSTAR departments of GSI and HIM (Helmholtz Institute Mainz) are integral part of the NUSTAR Collaboration and they participate in and contribute to the experiments with intense stable beams and with exotic nuclei at GSI-FAIR. They are also part of the research topic "Cosmic Matter in the Laboratory" of the Helmholtz program "Matter and the Universe". The NUSTAR mid-term strategy aims at the exploitation of new high-level scientific opportunities at the existing GSI accelerator facility using the novel equipment for FAIR, which is already available, and a continuous transition from GSI to FAIR as soon as the Super-FRS becomes available. Presently preparations for the transition phase are getting started. The main research instruments and experimental areas at GSI-FAIR are located at SHIP/SHIPTRAP, TASCA, FRS, ESR-Cryring, and R3B in Cave-C. The respective research groups of GSI and HIM perform a world-leading research program addressing nuclear structure far-off stability, nuclear astrophysics, reaction studies with exotic nuclei, and physics and chemistry of superheavy elements.

All DESPEC, R3B and Super-FRS EC experiments of the FAIR Phase-0 campaign scheduled in the first half 2022 at GSI/FAIR were successfully completed. Further extended set-ups were exploited, allowing for important new physics results. In particular, for the first time, the WASA detector was used at the FRS, the Foot Si tracker and LH2 target were employed in the R3B set-up and an array of 10 DEGAS Triple Ge gamma detectors as well as the DTAS total absorption spectrometer were employed in DESPEC. The "NUSTAR Beam Team", assembled from participants from the FRS, Nuclear Spectroscopy and Nuclear Reaction departments of GSI, the Super-FRS project group and several members of the NUSTAR Collaboration, was trained and contributed to all FRS experiments. An effort for consolidating this team is needed in coming years and additional participants are very welcome. The scientific strength and width of the NUSTAR Collaboration was impressively reflected by numerous proposals that were presented to G-PAC in fall 2022. Besides performing exciting physics experiments, the granted beam time will help to maintain and further develop the expertise of young researchers, which is the key for FAIR experiments in future.

Figure 32. The on-site participants of the NUSTAR Collaboration Meeting in September 2022 at GSI-FAIR. (Photograph: Claus Völker)

The NUSTAR Annual Meeting 2022, which was supposed to take place end of February, had been postponed on short notice due to the start of the war in Ukraine. As a consequence, the NUSTAR Annual Meeting was merged with the NUSTAR Week and finally the NUSTAR Collaboration Meeting 2022 was held at GSI from September 19 to 23. Being a hybrid meeting, many participants were able to come to GSI (see Figure 32), meeting with the colleagues who were joining in via video-conference. At the meeting, the latest developments of the FAIR NUSTAR project and Phase-0 experiments were presented and discussed.

Figure 33. Jonas Karthein (left) and Emma Haettner (right). (Photograph: Claus Völker)

During the NUSTAR Collaboration Meeting 2022, there was also the presentation of the FAIR-GENCO awards (Figure 33): Dr. Jonas Karthein of the Massachusetts Institute of Technology (MIT), USA, received the FAIR-GENCO Young Scientist award for applying the superior phase-imaging ion cyclotron resonance technique to short-lived nuclides, reaching relative mass uncertainties of 10^{-9}, the application to neutrino-less double beta decay, and for pursuing new applications using radioactive molecules. In addition, Dr. Emma Haettner of GSI/FAIR received the FAIR-GENCO Membership Award for her decisive role in recent improvements of the Fragment Separator FRS for experiments in FAIR Phase-0 and for the development of the new medical-physics program using radioactive beams for improved PET imaging.

4.1 FRS/SFRS

Head: Prof. Dr. Christoph Scheidenberger (JLU Gießen & GSI)
Authors: Timo Dickel, Emma Haettner, Daria Kostyleva, Kenta Itahashi, Ivan Mukha, Martin Bayzek, Sivaji Purushothaman, Take Saito, Christoph Scheidenberger

The FRS department is integral part of the Super-FRS Experiment Collaboration, which is one of the approved FAIR collaborations within NUSTAR and which aims at exploiting the FRS (and later the Super-FRS) as high-resolution spectrometer for relativistic primary and secondary beams. The experimental program ranges from new-isotope search experiments to applications and addresses selected key questions at the intersect of atomic, nuclear and hadron physics.

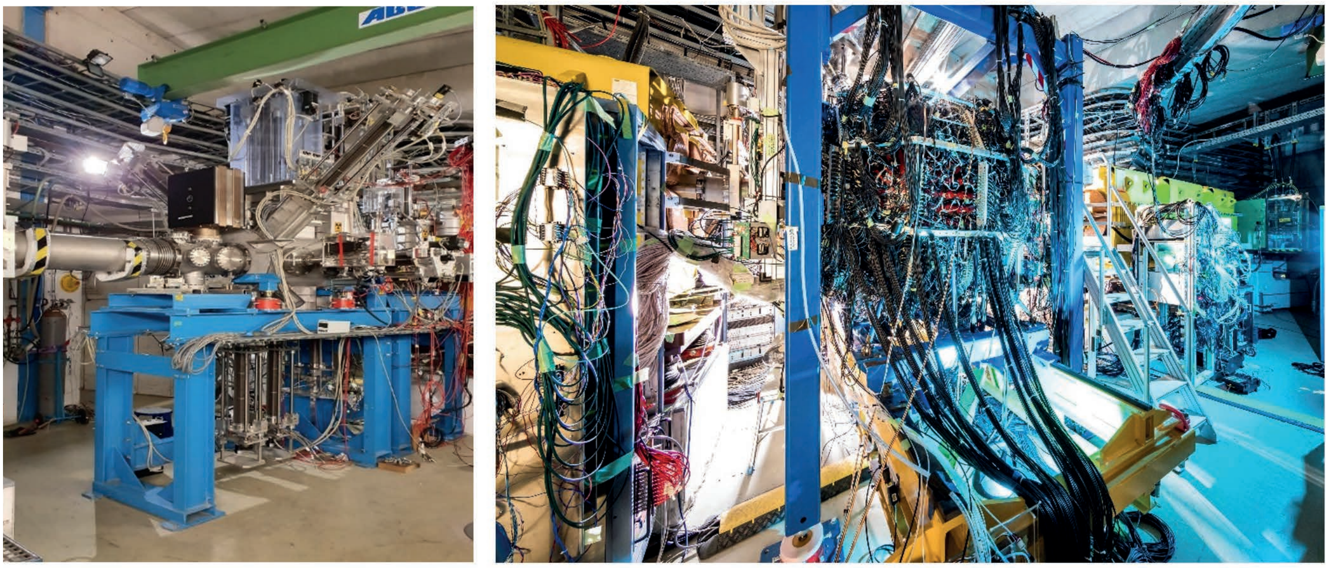


Figure 34. Left: FRS mid-focal plane with the standard equipment for isotope separation and identification, view in July 2021. Right: December 2021 with WASA and ancillary detectors integrated at the FRS mid-focal place.

The highlight experiments in 2022 were studies of light hypernuclei and the search for η'-mesic nuclei. For these experiments, special efforts were made to integrate the WASA detector at the FRS mid-focal plane and combine the capability of tracing light decay particles in coincidence with the high-resolution momentum analysis of heavy reaction or decay residues. Figure 34 shows a photo before and after installation of the WASA detector. In this configuration, two experiments could be successfully accomplished. The WASA campaign was followed by a very short reconfiguration phase of the setup in order to enable the other 6 NUSTAR experiments at FRS using fragment beams.

Overall, the FRS department was involved in 10 different experiments with GSI beams in 2022. Most of them took place at the FRS, one was performed at the UNILAC, in addition internal sources were used for experiments. Like in previous years, the NUSTAR experiments with FRS beams were supported by the NUSTAR Beam Team, which in total contributed with approximately 4,100 hours for preparations and running of these experiments. The analysis of the experiments performed in FAIR Phase-0 in years 2020 and 2021 is underway. Some preliminary results are presented below together with the major activities pursued in 2022.

Highlights in 2022

Experiments with WASA@FRS

After the removal of the FRS standard equipment at its central focal plane in summer 2021, the WASA detector was mounted together with associated ancillary, partly newly developed detectors and the cryogenic system of the superconducting solenoid at the mid-focal plane (F2) of the FRS. A photograph of the setup is shown on the right side of Figure 34. The preparations were completed by the end of January 2022 and followed by a commissioning run with proton beams that was performed within a week in late January and early February. After the commissioning, two experiments were performed in February and March 2022, respectively.

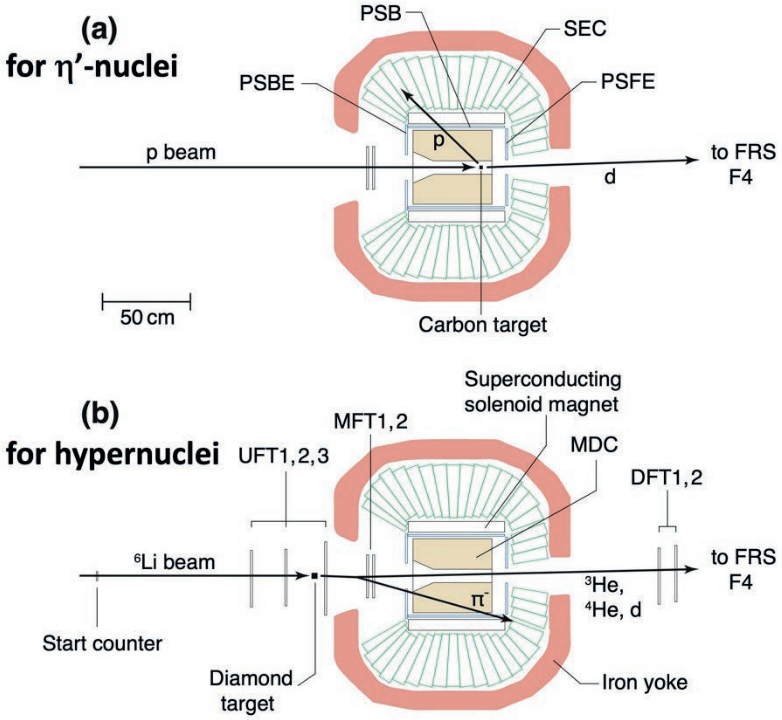


Figure 35. Experimental configurations of the S490 experiment for searching for eta'-nuclei (panel (a)) and the S447 experiment for studying hypernuclei (panel (b)).

The first experiment (S490) was performed in February and aimed to study an exceptionally large mass of the eta' meson, which has been an unsolved issue in quantum chromodynamics (QCD). To investigate the origin of the eta' mass in view of the low-energy QCD, it is important to place an eta' in different environments, ultimately in the high-density condition of nuclear matter. Theoretically, the mass of the eta' is expected to change in the nucleus due to the partial restoration of the chiral symmetry in the nucleus. The experiment was performed with an eta' meson bound to a carbon nucleus. A high-energy proton beam was accelerated by the SIS18 and impinged on a carbon target located at the central focal plane of FRS to form eta' mesons bound to the carbon nucleus, resulting in a deuteron escaping in forward direction. The deuterons were identified and momentum-analyzed by the second half of the FRS to measure the mass spectrum of the reaction products. The WASA detector was employed to identify the eventually produced eta'-nucleus bound states efficiently. Theoretical calculations show that the eta'-nucleus bound states decay by emitting a high-energy proton. The magnetic field of WASA analyzes the momentum of the emitted particles. Plastic scintillation counters of WASA were used for particle identification of the protons. Panel (a) of Figure 35 shows a schematic overview of the experimental setup for the S490 experiment. The WASA central detector used in the experiment consists of a super-conducting solenoid magnet (up to 1 Tesla magnetic field strength) with its associated iron yokes and a cryogenic system, a calorimeter with CsI crystals (SEC), an inner drift chamber with straw tubes (MDC), and newly developed arrays of plastic barrel hodoscopes (PSB) [Sek22] and end-cap hodoscopes (PSFE and PSBE) [Eka22]. Approximately $1\cdot10^7$ events of the ^{12}C(p,d) reaction were recorded in a data collection time of 62 hours.

The second experiment (S447) was performed in March 2022. Goals of the experiment are to measure the lifetime of hypertritons accurately and to confirm whether a bound state with two neutrons and a Λ hyperon does exist. The physics motivation and details of the experiment are discussed in [Sai21]. The configuration of the S447 experiment is shown in Panel (b) of Figure 35. In addition to the WASA setup employed in the first experiment (S490), additional scintillating fiber detectors are mounted [Eka22]. Three fiber detector stations, UTF1,2, and 3, were mounted in front of the WASA detectors, and two fiber detector stations, DFT 1 and 2, were placed behind the WASA detector. The mini-fiber detector composed by two fiber complexes (MFT1 and 2) was located inside the iron yoke of the WASA super-conducting solenoid magnet. A small hodoscope composed of small plastic scintillator fingers (referred as start counter in the figure) was mounted in front of the UFT1 to measure beam particles. Hypernuclei of interest, including the hypertriton and states associated with the nnΛ configuration, were produced by ^{6}Li and ^{12}C beams, respectively at bombarding energies of 1.96 GeV/u in a diamond target (areal thickness of 10 g/cm^2) located between the UFT2 and UFT3. Negatively charged pions from decays of hypernuclei are measured by the WASA detectors with the UFT3, MFT1 and MFT2, and residual nuclei of hypernuclear decays are transferred to and analyzed by the second half of the FRS behind the mid-focal plane (F2-F4). It should be noted that the standard resolving power of the FRS is close to 10^4 for the measurement of the momentum of the residual nuclei, which is approximately three orders of magnitude better than the former HypHI experiment in 2009. We have recorded 3.3·108 events with ^{3}He at F4, 0.9·10^9 events with ^{4}He at F4 and 1.8·10^8 events with deuterons at F4 by using ^{6}Li projectiles, in time periods of 41, 44 and 44 hours, respectively. Additionally, data with ^{12}C beams with an amount of 1.0·10^8 events were recorded with ^{3}He at F4 and 2.4 10^5 events with ^{9}C at F4 for 13.5 hours.

The data analysis is in progress. Light charged particles such as protons and $\pi^\pm$ mesons have been clearly identified. Further data analyses including event reconstructions for studying eta'-nuclei and light hypernuclei are in preparation.

- [Sek22] R. Sekiya et al., Nucl. Instruments Methods Phys. Res. A 1034, 166745 (2022)
- [Eka22] H. Ekawa for the WASA-FRS collaboration, EPJ Web of Conferences 271, 08012 (2022)
- [Sai21] T.R. Saito et al., Nat. Rev. Phys. 3, 803–813 (2021).

Experimental studies of proton-unbound light nuclei via in-flight decay spectroscopy at the FRS

The main activity here is related to scientific-technical developments of the experimental program and corresponding detection techniques for EXPERT experiments at the Super-FRS. Two experiment proposals were suggested and accepted to be performed as pilot studies at the FRS:

1. Experiment G-22-00115 “Study of a nuclear sandbank at the proton unbound bromine isotopes”. Spectroscopy results of ^{69}Br, that were obtained in the preliminary analysis of data measured during detector tests (combined experiments S443 and S459), constituted the basis for this proposal.

2. Experiment G-22-00111 “Towards limits of nuclear structure by using a ^{9}C beam”. The experimental results on ^{6}H-^{7}H published in Ref. [1] are cornerstones of the proposal.

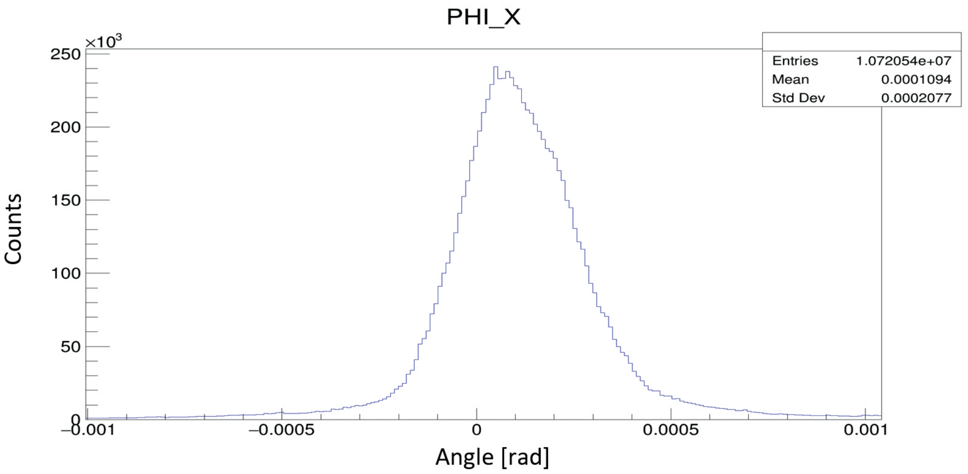


Figure 36. Horizontal angular distribution of 160 GeV muons tracked by six micropixel detectors relative to the beam axis during the AMBER beamtime at CERN. An angular uncertainty of 0.2 mrad (standard deviation) has been derived in a preliminary data analysis.

Both experiments shall be performed in the upcoming beamtime period by tracking the reaction products with the new generation micro-strip detectors FOOT and micro-pixel ALPIDE detectors. FOOT detectors were successfully implemented in the joint R3B experiments S509 and S522 in May 2022. Stable conditions for the detection of protons and light ions were achieved. Improved front-end boards, new-developed FPGA firmware and the DAQ software were tested and commissioned. The ALPIDE detectors were first tested with 1 GeV/u d, p beams at COSY (Jülich) in March 2022 in cooperation with R3B and ALICE collaborations. The DAQ software and part of the firmware of the MOSAIC FPGA readout board were developed and implemented in the GSI DAQ system. Several tests of ALPIDE detectors using radioactive sources followed in summer 2022. The second test with 160 GeV muons was done together with the AMBER collaboration at CERN in November 2022. Stable performance of six detectors at beam intensity up to 4 MHz was demonstrated. Clustering and tracking software developed for the experiments at GSI has been applied. The obtained tracking of muon trajectories had the angular resolution of ~0.2 mrad, which is illustrated in Figure 36.

FRS Ion Catcher offline campaign: Search for double alpha radioactivity in ^{224}Ra

After the discovery of alpha decay by E. Rutherford in 1899, more than 100 years ago, recent developments have focused on moving away from well-established empirical models to microscopic descriptions of alpha decay. Recent work by F. Mercier et al. [Mer21] has predicted that not only is the symmetrical double alpha decay more probable than the decay via the emission of 8Be, but also that the branching ratio should be accessible by current measurement techniques (BR ~ $3{\cdot}10^{-8}$). The discovery of double alpha decay would provide important support for the microscopic models that are also applied to nuclear structure phenomena, cluster states, spontaneous and induced fission, and alpha decay predictions.

The FRS Ion Catcher was used to investigate the decay of ^{224}Ra with an internal ion source with high statistics, as it provides long observation times and stable measurement conditions. In 2022, an experiment was started to measure the branching ratio of ^{224}Ra decays utilizing the thermalization of ^{228}Th alpha recoils in the cryogenic stopping cell (CSC) and the preparation of a beam of ^{224}Ra^{2+} ions from the CSC by a radio-frequency quadrupoles (RFQ) beamline. The ^{228}Th activity was ~30 kBq. After extraction from the CSC, the ^{224}Ra^{2+} ions were transported and filtered using a system of RFQs, resulting in a pure beam of ^{224}Ra^{2+}. The ^{224}Ra was then implanted on a 10 µg/cm^2 carbon foil in the center of a decay apparatus based on two double-sided silicon strip detectors (DSSD) from the University of Edinburgh. This detector recorded each alpha particle's position, time, and energy. Since the experiment was done with radioactive sources instead of a nuclear reaction at an accelerator, data taking over a long period was possible and more than 10^9 ^{224}Ra decays were observed. The data analysis is underway.

- [Mer21] F. Mercier et al. , Phys. Rev. Lett. 127, 012501 (2021)

MNT experiments with TOSCA

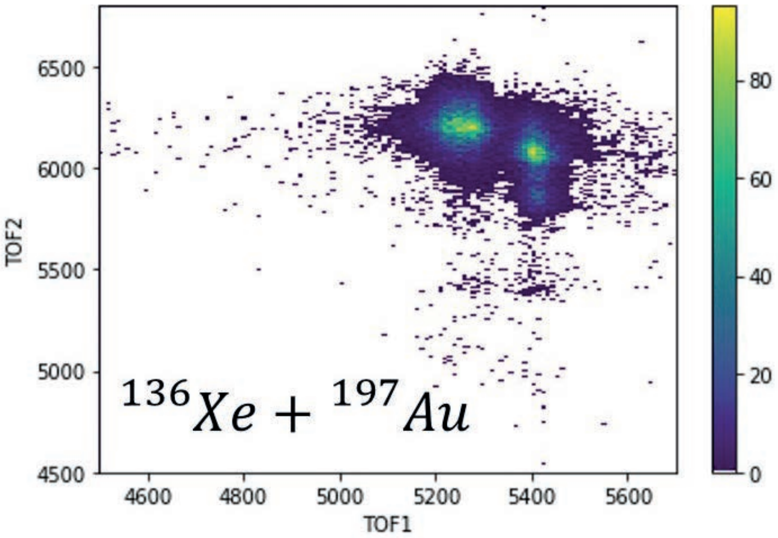


Figure 37. TOF1 vs TOF2 for the reaction ^{136}Xe on ^{197}Au measured with the TOSCA detector in UNILAC vault X6.

It is one of the long-term goals of the Super-FRS Experiment Collaboration to perform reaction studies at the Coulomb barrier exploiting the intense secondary beams of the Super-FRS. In particular, slowed-down beams of neutron-rich nuclei are considered favorable for producing even more-neutron-rich (and possibly new) isotopes via deep inelastic reactions, such as multi-nucleon transfer (MNT). As a preparatory step in order to gain physics insights in the reaction mechanisms and dynamics and in order to develop the theoretical background and framework, MNT experiments have been proposed using primary beams from UNILAC and newly developed setups, e.g. the two-arm detector TOSCA. The experiment U323 was performed with the goal to study the multiple nucleon transfer process at near-barrier energies in the two reactions ^{136}Xe + ^{197}Au and ^{136}Xe + ^{192}Ir, which may lead to neutron rich nuclei spreading in the “Terra Incognita” along the shell closure at N=126. The two different reactions are expected to gain insight on the nucleon transfer probability populating the same isobars starting from two different entrance channels.

Mass and energy distributions of binary reaction products were measured. Binary reaction products hitting the TOSCA detector pass through a thin aluminized mylar foil from which electrons are released and accelerated; an electrostatic mirror deflects these electrons by 90° and guides the on chevron mounted set of two microchannel plates, which multiply the electrons that finally hit a position-sensitive anode. The use of microchannel plates allows achieving a time resolution of ~150ps. With two arms and the use of the two-body kinematics, it is possible to reach a mass resolution up to 2…4 amu within a flight path of 20 cm. A time-of-flight spectrum of both arms obtained in the reaction ^{136}Xe + ^{197}Au is shown in Figure 37.

Results from previous FAIR Phase-0 experiments

Basic studies using positron emitters for ion-beam therapy

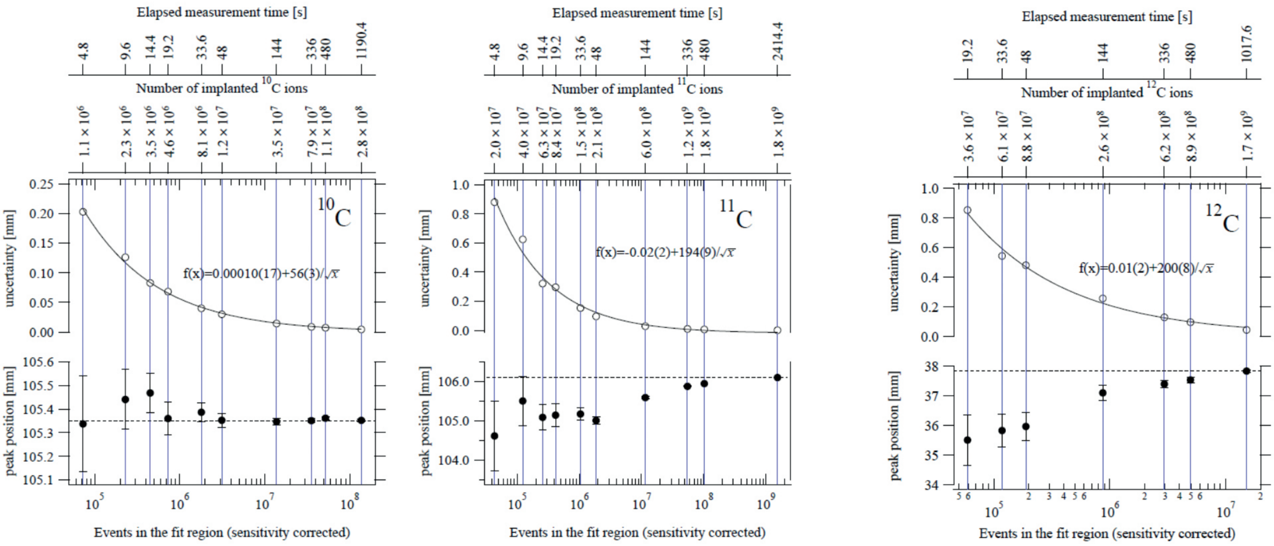


Figure 38. Measured peak position (solid circles) and related uncertainty (open circles) are shown as a function of the cumulative sum of counts (numbers over implantation cycles) and the elapsed measurement time (on top of the graphs). The left and center panel depict the irradiation with ^{10}C and ^{11}C beams with higher energy, respectively, and the right panel shows the results of the irradiation with ^{12}C beam at lower energy. The fit functions used for the description of the evolution of uncertainty are shown in the legend. The dashed line marks the peak position obtained after the longest measurement time and is to guide the eye.

The Super-FRS Experiment Collaboration continued the previously started experiments within BARB (this activity aims at Biomedical Applications of Radioactive ion Beams) and focused on the evaluation of high-quality, high-statistics in-beam PET images of ^{10}C, ^{11}C that were produced and separated in-flight with the FRS. The positron-emitting nuclei were implanted into a PMMA phantom (plexi glass) with therapy-relevant energies and imaged using a dual-panel PET scanner, which was provided by the University Medical Center Groningen (The Netherlands). Taking advantage of the high statistics obtained in this experiment, the focus lies on time evolution of the uncertainty of the range determined by means of PET during the course of the irradiation [Kos22]. For example and as shown in Figure 38, the range uncertainty derived from the PET activity of ^{10}C, ^{11}C and ^{12}C decreases quickly within the data taking period and the radioactive ions provide sub-millimeter precision within few seconds. It can be concluded that this uncertainty is fully determined by the PET counting statistics, which is directly related to the half-life of ^{10}C and ^{11}C. Because of the much shorter half-life of ^{10}C in comparison to ^{11}C, a precise knowledge on the range of the beam is achieved much faster when using ^{10}C than ^{11}C or ^{12}C.

- [Kos22] Kostyleva, D., et al. "Precision of the PET activity range during irradiation with 10C, 11C, and 12C beams." Physics in Medicine & Biology 68.1 (2022): 015003.

Outlook for 2023

The data analysis of the two performed WASA@FRS experiments (S447 and S490) and of all other experiments performed in the framework of the Super-FRS Experiment Collaboration will continue. Feasibility and simulation studies for measuring the hyper-nuclear radius via total interaction cross sections will be performed. Detector tests and developments for EXPERT will continue with on-site acceptance tests of the GADAST gamma-ray detectors (contribution of Czech Republic to FAIR) and tests of the new large-area ALPIDE detectors at COSY (Jülich); the design of a scattering chamber for housing the FOOT/ALPIDE detectors at FRS is planned. The FRS Ion Catcher will be prepared for tests of the helium recovery unit (HRU, Finnish in-kind contribution to FAIR) for the Cryogenic Stopping Cell of the Super-FRS; off-line experiments on double-alpha decay (analysis) and studies of fission fragments (analysis and measurement runs) from an internal source will continue. The NUSTAR Beam Team will continue to prepare the engineering run in fall 2023 and FRS experiments in 2024 and 2025, respectively.

Selected publications of 2022

- [1] Kaur, S. ; Kanungo, R. ; Horiuchi, W. ; et al.:Proton Distribution Radii of $^{16-24}$O : Signatures of New Shell Closures and Neutron Skin. Physical review letters 129(14), 142502 (2022), DOI:10.1103/PhysRevLett.129.142502
- [2] Porter, W. S. ; Ashrafkhani, B. ; Bergmann, J. ; et al.: Mapping the N = 40 island of inversion: Precision mass measurements of neutron-rich Fe isotopes. Physical review / C 105(4), L041301 (2022), DOI:10.1103/PhysRevC.105.L041301
- [3] Rodríguez-Sánchez, J. L. ; Benlliure, J. ; Vidaña, I. ; et al.: Systematic study of Δ(1232) resonance excitations using single isobaric charge-exchange reactions induced by medium-mass projectiles of Sn. Physical review / C 106(1), 014618 (2022), DOI:10.1103/PhysRevC.106.014618
- [4] Sekiya, R. ; Drozd, V. ; Tanaka, Y. K. ; et al.: Time resolution and high-counting rate performance of plastic scintillation counter with multiple MPPC readout. Nuclear instruments & methods in physics research / A 1034, 166745 (2022), DOI:10.1016/j.nima.2022.166745
- [5] Spătaru, A. ; Hornung, C. ; Dickel, T. ; et al.: First coupling of the FRS particle identification and the FRS-Ion Catcher data acquisition systems: The case of ^{109}In. Nuclear instruments & methods in physics research / B 522, 32 - 37 (2022), DOI:10.1016/j.nimb.2022.04.003

4.2 Nuclear reactions R3B

Head: Prof. Dr. Thomas Aumann (TU Darmstadt, GSI)
Authors: T. Aumann, A. Le Fèvre, K. Agarwal, W. Trautmann

The department Nuclear Reactions develops and operates the R3B (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 R3B experiment has been installed in Cave C at GSI while completion of the detector construction is still ongoing. For the FAIR Phase-0 production beam-time in 2022, the setup has been further completed by adding a new Silicon-microstrip vertex detector surrounding the target and a large-area Resistive-Plate Chamber RPC for proton time-of-flight measurement behind GLAD. For the foreseen beam time in 2024, the preparation of further advancements of the detection systems have been started, in particular, a further increase of the neutron detection capabilities of NeuLAND.

Highlights in 2022

The R3B NeuLAND demonstrator has been successfully commissioned with beam and efficiency-calibrated with monoenergetic neutrons at the RIBF in RIKEN some years ago. The detector was integrated in the SAMURA setup increasing the neutron-detection capabilities at SAMURIA substantially. During the two-years campaign at the RIBF with NeuLAND, several experiments with light drip-line nuclei have been performed, in which the R3B detector could demonstrate its unprecedented performance in terms of resolution. The scientific highlights from this campaign are the first observation of the tetraneutron, and the first invariant-mass measurement with four neutrons in coincidence with the remaining charged particle. The latter allowed the first observation of the ground state of the unbound ^{28}O nucleus located four neutrons beyond the drip line, as well as the first measurement of the four-neutron decay of the Coulomb-excited dipole continuum of ^{8}He. Both results are currently prepared for publication.

The experimental search for isolated multi-neutron systems has been an ongoing quest for several decades, with a particular focus on the four-neutron system called the tetraneutron, resulting in only a few indications of its existence so far, leaving the tetraneutron an elusive nuclear system for six decades. Here we report on the observation of a resonance-like structure near threshold in the four-neutron system that is consistent with a quasi-bound tetraneutron state existing for a very short time [1].

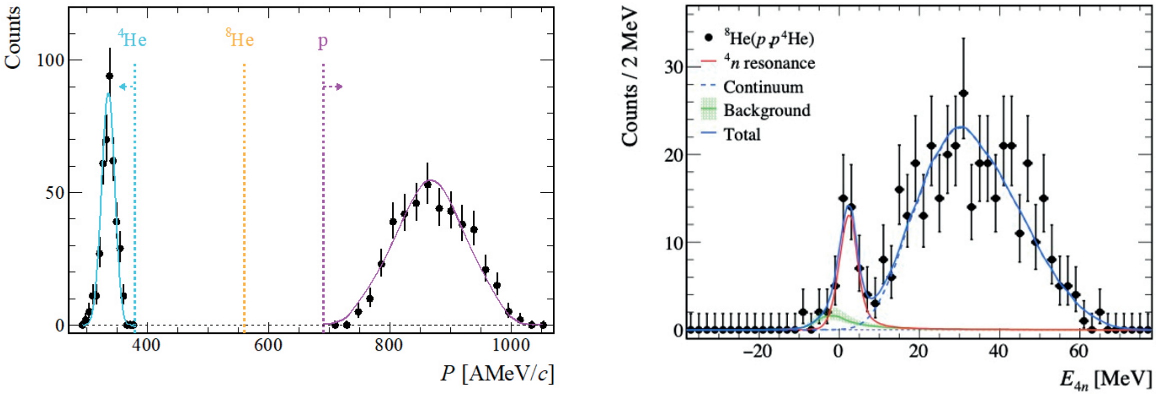


Figure 39. Left: measured momenta of the knocked-out ^{4}He and the scattered proton after the quasi-elastic scattering (symbols) compared to the initial momentum of the ^{8}He beam (yellow dotted line). Right: missing-mass spectrum of the four-neutron system extracted from the ^{8}He(p,pα) reaction. The different curves represent a Breit–Wigner resonance (pink), a non-resonant continuum (dashed blue), the background from two-step processes (green), and the total sum (solid blue). Figure adopted from Ref. [1].

The four-neutron system was populated in a quasi-elastic knockout reaction of ^{4}He from an ^{8}He beam impinging a liquid-hydrogen target. The experimentally chosen kinematics selected reactions with the largest possible momentum transfer, i.e., 180-degree scattering in the center-of-mass system, in order to minimize possible effects of final-state-interaction of the neutrons with the scattered charged particles. This resulting separation in momentum space can be seen in the left panel of Figure 39, where the momenta of the outgoing charged fragments ^{4}He and proton are shown in comparison to the ^{8}He beam momentum, which represents also the average momentum/nucleon of the unperturbed four-neutron system continuing flying in beam direction.

The energy of the four-neutron system has been determined from a precise measurement of both charged fragments using the missing-mass method. The invariant-mass measurement of the four neutrons was not possible due to the low cross section resulting from the selection of the kinematics, and the limited detection efficiency of around 1% for the four-neutron measurement. The neutron measurement, however, provided a consistency check in the 1n and 2n channels. The reconstructed energy spectrum of the four-neutron system, shown is the right panel of Figure 39, shows a well pronounced resonance-like structure close to the threshold at around 2 MeV and a broad bump centered around 30 MeV, which reflects the energy distribution among the neutrons in the ^{8}He ground state. The blue curve represents a theoretical estimate of the non-resonant contribution based on the COSMA model (L.V. Grigorenko et al., Eur. Phys. J. A 19 (2004) 187). While the observed peak energy is in agreement with some theoretical calculations, many other calculations based on different approaches do not find an indication for a resonant state in the 4n system. In order to finally understand the origin of the observed four-neutron correlation and its structure further theoretical and experimental attempts are called for.

Constraining Neutron-Star Matter — Combination of heavy-ion experiments, astronomy and theory

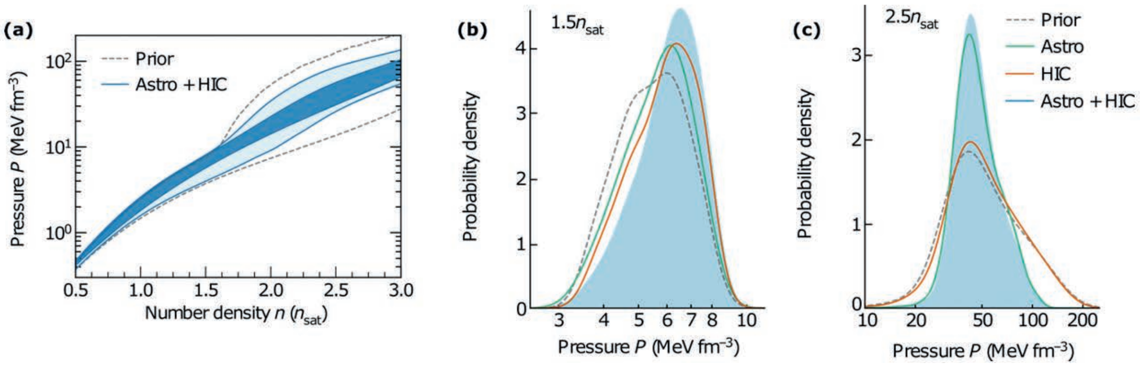


Figure 40. (a) Neutron star equation-of-state, in terms of pressure as a function of baryon density in units of nsat, obtained by combining nuclear theory ("Prior"), astrophysical observations and heavy-ion collisions ("Astro + HIC") within a Bayesian inference framework. (b) Corresponding probability density function of the pressure at $1.5n_{sat}$. (c) Idem at $2.5n_{sat}$. Figure adapted from [2].

For the first time, an international research team, including researchers from R3B and CBM, has combined data from nuclear physics experiments, gravitational wave measurements, and electromagnetic observations of neutron stars with theoretical insights to more precisely constrain the conditions of nuclear matter as it can be found in the interior of neutron stars. This study has been released in Ref. [2]. Neutron stars and their collisions are a unique laboratory to study the properties of matter at densities far above the nuclear saturation density (n_{sat}). Similarly, while not reaching such extreme conditions, heavy-ion collision experiments at GSI produce and probe densities above n_{sat}. Therefore, they provide a complementary way to produce and probe matter at high densities and under extreme conditions. Combining knowledge from nuclear theory, nuclear experiment, and astrophysical observations is essential for shedding light on the properties of neutron-rich matter over the entire density range found in neutron stars.

Constraints from collisions performed at GSI with KaoS, FOPI and ASY-EOS (R3B) experiments show a remarkable consistency with astrophysical observations even though they are obtained with completely orthogonal methods (see Figure 40). Including data of heavy-ion collisions in the analyses has enabled additional constraints near $1.5n_{sat}$ where nuclear theory and astrophysical observations are less sensitive. This has helped to provide a more complete understanding of dense matter.

In the future, improvements of constraints from heavy-ion collisions can play a key role to bridge informations from nuclear theory and astrophysical observations. Especially experiments that probe higher densities while reducing the experimental uncertainties, like the R3B project of a second generation of ASY-EOS experiments — benefiting in particular from the high performance of the neutron detector NeuLAND — have great potential to provide new constraints of neutron star properties at around $2.5n_{sat}$ where results are currently driven by astrophysical observations. At the new FAIR facility, R3B will provide unique opportunities to produce and study neutron-rich matter at densities comparable to those in the interior of neutron stars or in neutron star mergers. These perspectives have recently been reviewed in Refs. [3] and [4].

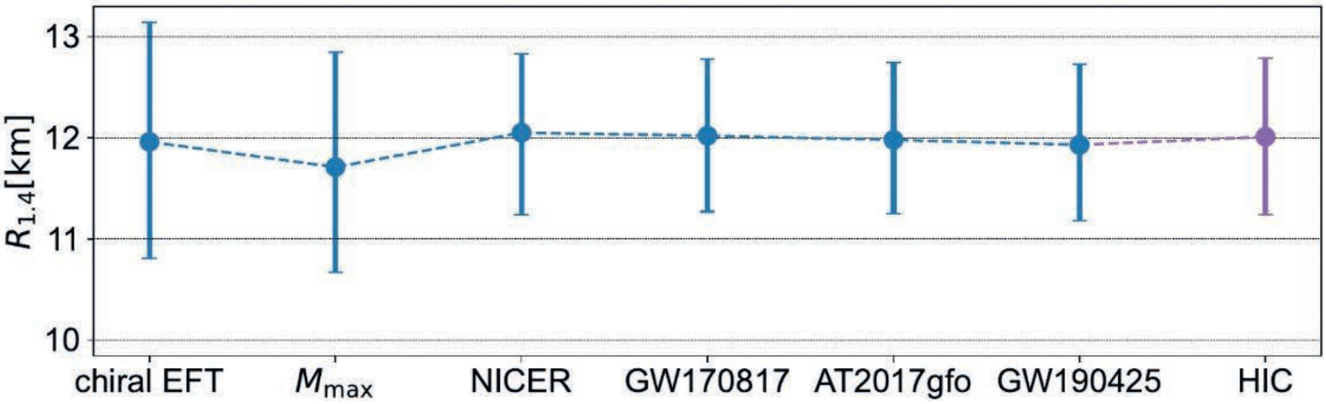


Figure 41. Radius of 1.4-solar-mass neutron stars as increasingly constrained by (from left to right) nuclear theory (chiral EFT), various astrophysical observations, and heavy-ions collisions (HIC); extracted from Ref. [1].

Further highlights are the quasi-free proton-knockout reactions with the two-proton halo candidate ^{17}Ne, and the completion of the development, construction, and full characterization of the new R3B time-of-flight detector, which has been summarized in Ref. [6]. The experiment of knockout reactions of ^{17}Ne could thanks to its exclusive measurement clarify a long-standing discussion on the halo character of this nucleus and its configuration mixing in the halo-proton ground-state wavefunction. A consistent determination of the fractions of l=0 and l=2 motion of the valence protons has been achieved by using two independent observables. With a resulting relatively small l=0 component of only around 35(3)%, it is concluded that ^{17}Ne exhibits a rather modest halo character only.

FAIR Phase-0: experiments

R3B scheduled two experiments in the Phase-0 beam time in 2022 including the first experiment studying short-range nucleon-nucleon correlations (SRC) with a radioactive beam. As the first case, measurements for the neutron-rich nucleus ^{16}C and for comparison for the stable ^{12}C have been conducted. Aim is to quantify the effect of the neutron excess by a direct comparison of nuclei with similar mass but different A/Z. For stable nuclei, a pronounced dependence of SRC on mass-to-charge ratio has been reported from JLAB experiments (M. Duer et al., Nature 560 (2018) 617). However, the fact that more neutron-rich stable nuclei are at the same time also heavier prohibit to disentangle the effects of asymmetry and mass. The R3B experiment provides an exclusive and kinematically complete measurement of the reaction products, including the scattered protons from the (p,2p) quasi-free reaction, as well as the heavy residue and the recoiling partner nucleon of the knocked-out SRC pair. Last year we reported here the result from the first step in this direction, an inverse kinematics experiment identifying SRC pairs using a high-energy stable beam at the JINR (M. Patsyuk et al., Nature Physics 17 (2021) 693).

The second experiment aimed at a search for multi-neutron cluster threshold resonances in the continuum of light neutron-rich nuclei. The excited continuum is in this experiment populated using the quasi-free proton knockout reaction. Both experiments used an almost identical configuration of the R3B setup. In particular, a newly introduced vertex tracker based on FOOT silicon micro-strip detectors surrounding the liquid-hydrogen target. These two experiments were the first using this newly developed system. Further developments of this device are currently ongoing for use in the beam time in 2024.

Outlook for 2023

During 2023, the R3B setup will be further developed and completed to prepare for the 2024 Phase-0 beam time. In particular the further development and re-configuration of the FOOT silicon tracker mentioned above, and the further construction of NeuLAND double planes which will provide an increased neutron detection efficiency. A commissioning run and two experiments are foreseen to be performed in spring 2024. One will be again dedicated to the study of SRC, but using a complementary method, the (p,pd) deuteron knockout reaction. Several carbon isotopes spanning a wide range in A/Z will be measured. The comparison with the results from the (p,2p) reaction discussed above will provide important information for a consistent understanding of SRC. The second experiment is devoted to the investigation of the hyperon-nucleon interaction. As a first experiment in this program at R3B the hyper-triton will be produced by $^{12}C+^{12}C$ collisions. The experiment aims at the determination of the radius of the hyper-triton by a measurement of its total reaction cross section. For this measurement, a newly developed Time-Projection Chamber will be inserted into the GLAD dipole.

Selected publications of 2022

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- [2] Huth, S. ; Pang, P. T. H. ; Tews, I. ; et al.: Constraining neutron-star matter with microscopic and macroscopic collisions. Nature <London> 606(7913), 276 - 280 (2022), DOI:10.1038/s41586-022-04750-w
- [3] Russotto, P. ; Cozma, M. D. ; De Filippo, E. ; et al.: Studies of the equation-of-state of nuclear matter by heavy-ion collisions at intermediate energy in the multi-messenger era. Rivista del nuovo cimento 46(1), 1 - 70 (2023), DOI:10.1007/s40766-023-00039-4
- [4] Sorensen, A. et al.: Dense Nuclear Matter Equation of State from Heavy-Ion Collisions. arXiv nucl-th 2301.13253
- [5] Lehr, C. ; Wamers, F. ; Aksouh, F. ; et al.: Unveiling the two-proton halo character of ^{17}Ne: Exclusive measurement of quasi-free proton-knockout reactions. Physics letters / B 827, 136957 (2022), DOI:10.1016/j.physletb.2022.136957
- [6] Heil, M. ; Kelić-Heil, A. ; Bott, L. ; et al.: A new Time-of-flight detector for the R3B setup. The European physical journal / A 58(12), 248 (2022), DOI:10.1140/epja/s10050-022-00875-8

4.3 Nuclear spectroscopy

Head: Dr. Jürgen Gerl (GSI) untill 31.08.2022, Dr. Magda Górska from 1.09.2022
Authors: M. Górska, H.M. Albers, J. Gerl, K. Wimmer

The structure of atomic nuclei is addressed by studying bound excited states and their decay in the Nuclear Spectroscopy Department. 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 nucleo-synthesis 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 PANDA collaborations among others, in addition we are 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(Riken Nishima Center, Japan), FRIB (Michigan State University, US), INFN-LNL (Legnaro, Italy), GANIL (Caen, France), ISOLDE (CERN), and ILL (Grenoble, France). HISPEC in-beam spectroscopy experiments are currently in the test phase.

The DESPEC project [1] started within FAIR Phase-0 in 2020; the first scientific results are already published [2-4]. A significant developmental step was achieved for spectroscopy experiments with scintillation detectors in collaboration with the GSI electronic department as described in [5].

In 2022, two physics runs and two detector test experiments were granted beam time.

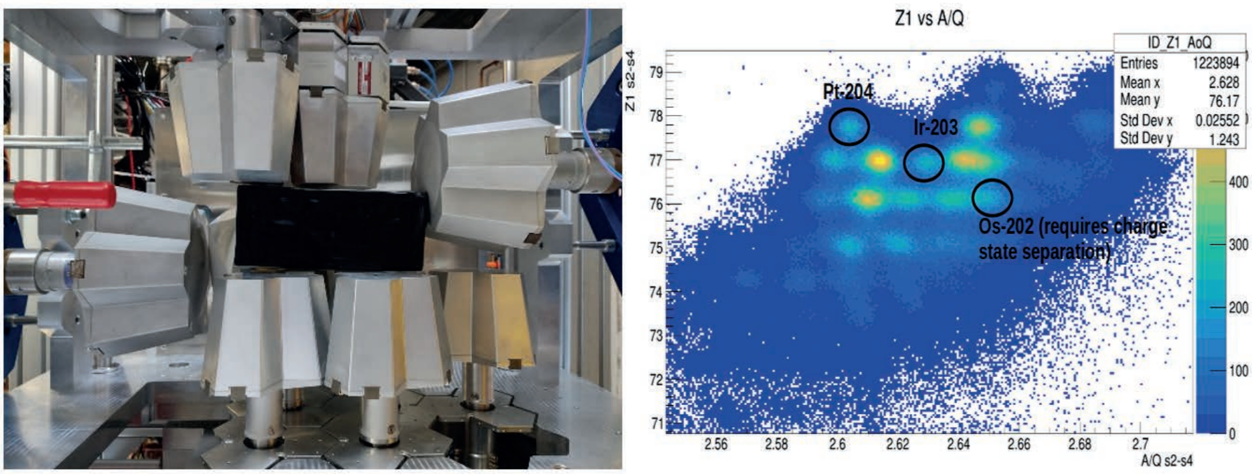

Figure 42. (left) Assembly of the DEGAS HPGe array and (right) the on-line FRS identification spectra of the N=126 isotones under investigation.

In May 2022, the first implementation of the DEGAS array in its standard geometry, where the triple clusters are placed parallel to each other in 4 perpendicular planes creating side walls of a “box”, was achieved, as can be seen in Figure 42. This configuration was used in experiment S450, wherein neutron-rich N~126 nuclei were populated. The statistics collected on the key nucleus ^{203}Ir is about 4-5 times larger than in previous work. The analysis is ongoing, with the goal to identify excited states in the exotic nucleus ^{202}Os.

In June 2022, the DTAS setup was implemented on the DESPEC Phase-0 experimental platform (see Figure 43) for the first time. Prior coming to GSI, the performance of the detector setup was improved in terms of modularity of the array (comprising 18 individual crystals), and a standalone data acquisition system, that was fully integrated into the

GSI MBS system. The analysis methods were also upgraded for treating β-intensity distributions, making the DESPEC-DTAS setup in combination with the FRS a unique opportunity to measure the full β-strength of neutron-rich nuclei across N=126 for the first time (experiment S505). This will provide information on the β-decay matrix elements in this region of nuclei and relate to the formation of the 3rd r-process abundance peak.

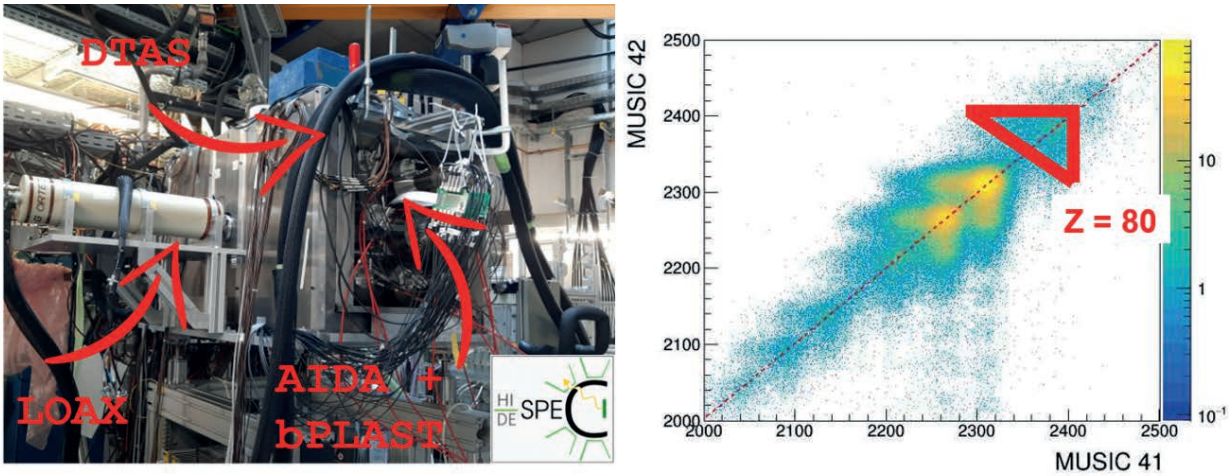

Figure 43. DTAS experimental setup and the on-line identification spectrum measured in experiment S505.

In addition to the DESPEC physics experiments, a test of a planar HPGe detector as an implantation material was performed in the experiment S506 for the first time. The measurement addressed the challenge to discriminate between signals from implantation events and low-energy gamma rays and internal conversion electrons, depopulating isomeric states. For this purpose, the decay of a milli-second isomer in ^{184}Pt implanted in the detector was investigated. In addition, damage effects due to heavy-ion irradiation were studied with an implantation rate of about 10 Hz. In Figure 44, the experimental setup is shown along with the detector pulses of different particles recorded with an the oscilloscope. The detector underwent a detailed scanning after the experiment and no major signs of damage were observed. The offline analysis is in progress.

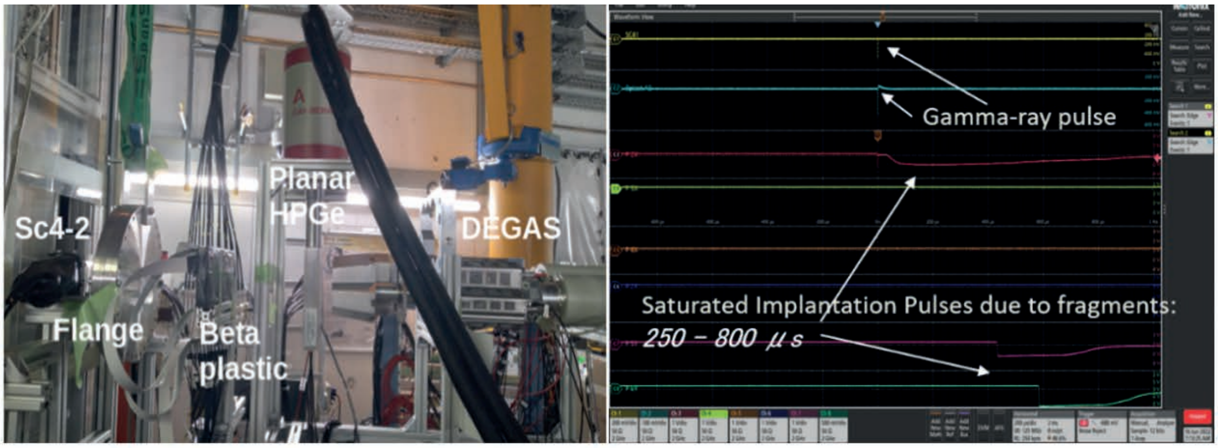

Figure 44. (left) Experimental setup of the test experiment and (right) the response of the implantation Ge detector to ions and electrons.

The HISPEC experiment was also reestablished after a long break caused by unsuitable experimental conditions. The first test concerned the development of a tracking detector for the slowed-down beam experiment. Stable beams degraded to about 10 AMeV were used to study the feasibility of identification and tracking of the beam and its products, including the angular and energy straggling. The suite of detectors used included the high-resolution cooled ΔE-E DSSD telescope and time-of-flight micro-channel plates. The data analysis is ongoing.

Within the LISA project, initial tests of the performance of single-crystalline CVD diamond detectors were conducted. Different readout schemes were compared aiming at achieving the highest energy resolution for the active target detectors. A lab test bench has been established, and the development of fast charge-sensitive pre-amplifiers is now ongoing.

In parallel to its other research programs, the department has further developed activities related to the application of machine-learning methods to improve detector performance in DESPEC experiments. In particular, nearestneighbour and regression algorithms (e.g. KDTrees, Multitarget artificial neural networks, etc) have been successfully applied to in-beam data collected during the DESPEC FAIR Phase-0 campaign in 2021 to significantly improve the position resolution of fast scintillation detectors with silicon photomultiplier readout. Additional projects, including the application of deep-learning methods to noise filtering and β-particle identification in double-sided silicon strip detectors, are planned for 2023.

Physics highlights of the group also include the commissioning of the AGATA setup at Legnaro National Laboratory [6] and the successful exploration of single-particle states in the fp-shell through the ^{50}Ca(d,p)^{51}Ca transfer reaction at RIBF. This experiment ties in with the ongoing efforts to explore shell-evolution and new magic numbers in the Ca isotopes toward the neutron-drip line (see below).

Highlights in 2022

Recent progress in experimental and theoretical approaches in the region of doubly-magic ^{100}Sn were reviewed in reference [7].

The nucleus ^{212}Po has been studied via isomer γ-decay spectroscopy with the RISING setup [8]. Two delayed previously-unknown γ rays have been observed. One has been attributed to the E3 decay of a 21^- isomeric state feeding the α-emitting 45-s (18+) high-spin isomer. The other γ-ray line has been assigned to the decay of a second, higher-lying 23^+ metastable state. These are the first observations of high-spin states above the ^{212}Po (18^+) isomer, thanks to the selectivity obtained via ion-by-ion identification of ^{238}U fragmentation products. Comparison with shell-model calculations points to shortfalls in the nuclear interactions involving high-j proton and neutron orbitals, to which the region around Z~100 is sensitive [8].

New high-resolution mass spectroscopy data taken during the HiCARI campaign explored the N=34 shell-gap reduction in the Ti isotopes [9]. It reveals that the empirical two-neutron shell gap at N=34 vanishes for Ti and V, and identify the enhanced N=34 energy gap as a feature unique to the Ca isotopic chain.

The observation of excited states in ^{55,57}Ca was reported in [10]. These are the most neutron-rich isotopes of calcium where spectroscopic studies could be made to date. In addition to energies, the lifetimes of the excited states were also determined. The surprising result is a transition from a single-particle dominated regime in ^{55}Ca next to the N=34 magic number to a collective nature ^{57}Ca, which can be regarded as a precursor to the N=40 island of inversion.

Outlook for 2023

Several results on technical developments as well as physics outcomes from the FAIR Phase-0 program and activities at other facilities are in preparation for publication in 2023. In view of the limited beam time available for physics runs, experimental activities planned at GSI include further preparation of the experimental apparatus for DESPEC as well as for the LISA project. In particular, newly-procured diamond detectors will be tested in Japan at the HIMAC facility followed by a test with radioactive beams at the FRS facility at GSI. The ongoing AGATA campaign at LNL is also one of the main focus points of our physics programme. The IDATEN campaign in RIKEN, which is expected to start in 2023, is of strong interest to the department and includes several co-spokespersons of planned experiments.

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- [2] Jazrawi, S. ; Yaneva, A. ; Polettini, M. ; et al.: Commissioning the FAst TIMing array (FATIMA) at FAIR Phase-0: Half-lives of excited states in the N=50 isotones ^{96}Pd and ^{94}Ru. Radiation physics and chemistry 200, 110234 (2022), DOI:10.1016/j.radphyschem.2022.110234
- [3] Polettini, M. ; Pellumaj, J. ; Benzoni, G. ; et al.: Decay studies in the A 225 Po-Fr region from the DESPEC campaign at GSI in 2021. 107th Congresso Nazionale della Societa Italiana di Fisica, SIF 2021, Online, Italy, 13 Sep 2021 - 17 Sep 2021 Il nuovo cimento / C 45(5), 125 (2022), DOI:10.1393/ncc/i2022-22125-5
- [4] Das, B. ; Cederwall, B. ; Qi, C. ; et al.: Nature of seniority symmetry breaking in the semimagic nucleus ^{94}Ru. Physical review / C 105(3), L031304 (2022), DOI:10.1103/PhysRevC.105.L031304
- [5] Banerjee, A. ; Wiebusch, M. ; Polettini, M. ; et al.: Analog front-end for FPGA-based readout electronics for scintillation detectors. Nuclear instruments & methods in physics research / A 1028, 166357 (2022), DOI:10.1016/j.nima.2022.166357
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- [7] Gorska-Ott, M.: Trends in the Structure of Nuclei near ^{100}Sn. Physics 4(1), 364 - 382 (2022), DOI:10.3390/physics4010024
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- [10] Koiwai, T. ; Wimmer, K. ; Doornenbal, P. ; et al.: A first glimpse at the shell structure beyond ^{54}Ca: Spectroscopy of ^{55}K, ^{55}Ca, and ^{57}Ca. Physics letters / B 827, 136953 (2022) DOI:10.1016/j.physletb.2022.136953

4.4 Superheavy elements at GSI and HI Mainz

**Department Heads: Prof. Dr. Michael Block (JGU Mainz, GSI, HI Mainz);
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Authors: Dominik Dietzel, Francesca Giacoppo, Manuel Gutiérrez, Jadambaa Khuyagbaatar, Tom Kieck, Jeremy Lantis, Mustapha Laatiaoui, Pavol Mošat', Danny Münzberg, Steven Nothhelfer, Valeria Pershina, Sebastian Raeder, Dennis Renisch, Jessica Warbinek, Yeqiang Wei, Alexander Yakushev**

In 2022, activities at GSI focused on the UNILAC beamtime within the FAIR Phase-0 program. These comprised chemistry studies of Nh, high-precision mass measurements of Fr and Bi nuclei and their progeny, on-line commissioning of the novel ANSWERS setup, and laser spectroscopy of Fm isotopes. In addition, the analysis of data obtained in previous beamtimes was continued. At HIM, the advancement of technical and methodological developments was most central, for example for applications in laser spectroscopy and mass spectrometry as well as radionuclide layer production for various applications.

Highlights in 2022

Synthesis/Nuclear reactions

An intense experimental nuclear reaction study program is carried out by the SHE-Chemistry department within an international collaboration. Analyses of experimental data on nuclear reaction dynamics by detecting fission fragments in the CUBE setup of the Australian National University's (ANU) Heavy Ion Accelerator Facility, Canberra, Australia are ongoing and will soon be published. Also, analyses of experimental data on multi-nucleon transfer reactions performed at the mass separator MARA of University of Jyvaskyla, Finland, were carried out.

Nuclear Structure

At TASCA, nuclear structure studies with the TASCA nominal large area focal plane detector are actively ongoing. In 2022, the experimental program on the study of K isomeric states was successfully continued, focusing on ^{250}No. In this nucleus, an isomeric state with a half-life of about 30 μs, which is longer than its 4-μs SF decaying ground state, is well-known. A direct fission from this isomeric state has not been observed yet, and an upper limit of 0.5 for the fission branch is established.

In the experimental work at TASCA [J. Khuyagbaatar et al., Phys. Rev. C 106, 024309 (2022)], a sensitive search for direct fission from the K isomeric state was performed. No direct fission branch from the isomeric state was identified, and a stricter value of 0.035 for the upper limit was deduced from data obtained in 2018. This shows that the fission from the high-K state can largely be hindered, and the hindrance-strength depends primarily on the properties of an individual nucleus. In addition, a signature for the presence of a higher-lying K isomeric state with a half-life of about 0.7 μs and decaying into the lower-lying one was observed. Based on this observation a second and higher-lying isomeric state has been suggested to exist in ^{250}No.

The intense experimental program studying high-K states in heaviest nuclei [J. Khuyagbaatar et al., Nucl. Phys A 994, 121662 (2020), Phys. Rev. C 103, 064303 (2021)] showed digital electronics to be advantageous for their identification and study. On the other hand, direct fission from a K-isomeric state in the heaviest nuclei is only known for two cases: ^{256}Fm and ^{254}No. These, however, do not represent the most extreme cases of bound many-body quantum systems. Therefore, the fission hindrance factor of high-K states is still poorly understood.

On the theoretical side, an approach to calculate the hindrance strength of the high-K number has been suggested and fission half-lives of various known and predicted high-K states in heavy and superheavy nuclei were calculated [J. Khuyagbaatar, Eur. Phys. J. A 58, 243 (2022)]. The results agreed well with various experimental data on the fission-stability of known K isomeric states. High-K states of nuclei with extremely short ground-state half-lives in the sub-μs range might ensure their survival during transport from production to detection. Therefore, the investigation of the high-K phenomena in the heaviest nuclei at TASCA is continuing.

DOI:10.15120/GSI-2023-00462

Meanwhile, an alternative method for the spectroscopy of the heaviest nuclei, which was suggested by the GSI's SHE-Chemistry department in 2020, is still under intensive development. In the 2022 FAIR Phase-0 beamtime, an upgraded version of the Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal (ANSWERS-v1) had been used for studies of Ac, Fr, Np and No isotopes. The obtained experimental data again confirm the spectroscopy potential of ANSWERS-v1. The data analysis is ongoing.

The previous experimental data accumulated with the ANSWERS-prototype in 2020, were finalized and are in preparation for publication. The analysis of the experimental data, e.g., the algorithm for trace-analysis, has been significantly improved. In addition, to advance our understanding of the system's response for multi-coincident events involving α-particles, electrons, protons and/or photons, simulations with the GEANT4 toolkit are being developed. The first version in which the ANSWERS-prototype was implemented was introduced in 2022 and its first simulated results are in fine agreement with the experimental responses. These results will be published and be used for the future optimization of ANSWERS.

The analysis of the SHIPTRAP data from the beamtime 2021 proceeded with the emphasis being on investigating low-lying isomeric states in the members of the α-decay chains ^{206}Fr – ^{202}At – ^{198}Bi and ^{204}Fr – ^{200}At – ^{196}Bi. In each of these nuclides two (low-lying) isomeric states were known from investigations by laser spectroscopy [K. M. Lynch et al. Phys. Rev. C 93, 014319 (2016)]. However, the excitation energy of these isomers remained unknown. We have observed both isomers and the ground state in all six nuclides and can directly determine the isomers' energies from the measured mass difference. The investigation of systematic uncertainties in mass measurements with SHIPTRAP has been advanced to support the analysis of the data from the 2021 beamtime and from offline measurements. The latter comprised measurements of decay products from ^{225}Ac and ^{223}Ra sources as well as mass measurements of ^{238}U, ^{242}Pu, and ^{244}Pu. The studies of the systematic uncertainties address mostly effects that are specific for the phase-imaging ion-cyclotron-resonance technique. Results from the 2018 SHIPTRAP campaign were recently published [O. Kaleja et al. Phys. Rev. C 106, 054325 (2022)]. Precise values of the masses of several No, Lr, and Rf isotopes were reported that also allowed improving the masses of 15 additional (super)heavy nuclides up to ^{271}Rg in the framework of the Atomic Mass Evaluation.

Atomic Physics

Laser spectroscopy studies on the heaviest elements continued in two experimental campaigns in April and May 2022. Using ^{40}Ar and ^{48}Ca beams from the UNILAC at GSI, atomic transitions in fermium (Z=100) and nobelium (Z=102) were investigated and the search for an atomic transition in lawrencium (Z=103) was continued. Due to recent advancements of the well-established RADRIS technique [J. Warbinek et al., Atoms 10 (2022) 41], more rare and short-lived nuclides like ^{251}No ($T_{½}$=0.8 s) and ^{246}Fm ($T_{½}$=1.4 s) could be studied. This, in combination with off-line measurements at Johannes Gutenberg University Mainz (JGU) allowed studies on a total of eight fermium isotopes ranging from ^{245}Fm to ^{257}Fm. The data analysis has been completed and a publication is in preparation. Further measurements at JGU comprised the study of long-lived isotopes of californium (Z=98) [F. Weber et al. "Probing the atomic structure of californium by resonance ionization spectroscopy." Atoms 10 (2022) 51] and einsteinium (Z=99) [F. Weber et al. "Atomic-structure investigations of neutral einsteinium by laser resonance ionization." Physical Review Research 4.4 (2022): 043053; S. Nothhelfer et al. "Nuclear structure investigations of $^{253-255}$Es by laser spectroscopy." Phys. Rev. C 105 (2022) L021302] revealing information on their atomic and nuclear structure. This work is a prerequisite for future measurements of short-lived Cf and Es isotopes at GSI.

In addition, an online commissioning experiment of the newly developed JetRIS setup [S. Raeder et al., Nucl. Instrum. Meth. Phys. Res. B, 463 (2020) 272] was performed. This novel apparatus was designed at HI Mainz to improve the spectral resolution for heaviest-element studies. To optimize the laser spectroscopy with improved resolution in the low density and low temperature environment of a supersonic gas jet effusing from the gas stopping cell the influence of the nozzle was studied in detail [D. Münzberg et al., Atoms 10 (2022) 57]. For the on-line experiment, major equipment such as a high-power and high-repetition rate laser system was contributed from external collaboration partners at KU Leuven and from HI Mainz. A laser spectroscopy experiment on ^{254}No was performed with JetRIS, demonstrating the feasibility of the novel approach improving the spectral resolution over that achievable with RADRIS [M. Laatiaoui et al., Nature 538 (2016) 495; S. Raeder et al., Phys. Rev. Lett. 120 (2018) 232503].

A long-term development at JGU and HIM, the novel Laser Resonance Chromatography (LRC) [M. Laatiaoui et al., PRL 125 (2020) 023002] method, aims at laser spectroscopy of superheavy ions, starting with lawrencium. Briefly, optical pumping of ions drifting in dilute helium is exploited to identify optical resonances. Successful excitation of ion levels triggers pumping to metastable states causing an abrupt change in transport properties that can be measured with drift time spectrometers [M. Laatiaoui et al., PRA 102 (2020) 013106]. For the best performance, experimental conditions must be found to maximize the mobility difference of the ground state and the excited state. This requires accurate theoretical constraints on the parameters in advance, in addition to preparatory off-line experiments. Using the Multi-Reference Configuration Interaction method, we predicted the electronic structure of Lr^+ and Rf^+ as well as the interaction potentials of the Lr^+-He and Rf^+-He systems [H. Ramanantoanina et al., PRA 104 (2021) 022813], [H. Ramanantoanina et al., Atoms 10 (2022) 48]. The interaction potentials are used to obtain the mobility of the ion drifting in helium in its ground state and lowest excited states. In parallel, simulations for ion bunching and drift have been performed to narrow down the working parameters of the LRC setup [E. Romero-Romero et al., Atoms 10 (2022) 87], which is still in the inauguration process, having installed the cryogenic drift tube and the miniature radio frequency buncher and ion guide. Initial results for transfer and bunching of ablated heavy ions work are promising. Optical pumping of Lu^+ ions will be next to establish the LRC method.

Chemical Studies

In the FAIR Phase-0 beamtime 2022, isothermal gas-phase chromatography experiments with alpha-decaying short-lived isotopes of Hg, At, and Po were carried out at TASCA to provide benchmark data for comparative studies with their superheavy homologs (Cn, Lv, Ts). The isolated isotopes were thermalized in a gas-filled volume behind TASCA and were flushed with noble gas streams through an isothermal chromatography column offering gold, quartz, or Teflon surfaces, the temperature of which could be varied in the range of about -70 to +150 °C. The fraction surviving transport through this column was measured in a COMPACT detector setup. All elements were found to interact strongly with the gold surface in the whole temperature range. At and Hg were mainly volatile on SiO_2, but also showed trends in the external chromatogram that clearly deviate from those resulting from Monte-Carlo-simulations performed for an assumed “mobile adsorption” interaction process. These new findings indicate a much more complex adsorption-desorption process, which could possibly be described as an interplay between chemisorption and physisorption.

Flerovium (Fl, element 114) is the heaviest element for which experimental chemical data have been published so far. To elucidate its chemical character and to settle differences in interpretation of experimental data obtained in two sets of experiments carried out by different collaborations, adsorption studies of Fl on silicon oxide and gold surfaces conducted at GSI were published in 2022 [1]. Evidently, two types of interaction of a Fl species with this surface were observed: chemisorption on Au at room temperature, and physisorption on ice. The inhomogeneous nature of the Au surface present in the experiment plays a key role. Two scenarios are able to explain the experimental observation: differences in bond strength of Fl atoms on an inhomogeneous Au surface, with the strength depending on the surface site, or the formation of a Fl compound (e.g. FlO). Both scenarios allow describing the complete experimental data set available on chemical properties of Fl, and they both imply that Fl forms chemical bonds and is hence rather a metallic element than a noble gas.

To allow studies of more short-lived superheavy nuclides, a fast buffer gas stopping cell to connect chemistry detection systems like COMPACT to TASCA is under construction. Ion trajectories simulations were carried out for this UniCell, which is based on the RF ion-funnel technique. Using optimized experimental parameters an extraction efficiency of about 100% resulted. The extraction time is calculated to be in the range of few ms for ions with a mass of 293 u and charge states of +1 and +2. In addition, simulations were also performed on an RF-only ejector-interface. The ejector extraction efficiency was optimized for various gas flow rates and RF frequencies/amplitudes. The transport time through the ejector is calculated to be about 2 ms. In a next step, COMSOL will also be employed to simulate the ion trajectories in the UniCell setup, and the construction will continue.

Chemical Theory Supporting Experimental Work

With the aim to interpret gas-phase experiments on the volatility of Fl [2] and nihonium (Nh, element 113) and its homolog Tl, calculations on the adsorption energy, E_{ads}, of MOH (M = Tl and Nh) on hydroxylated quartz surfaces were completed with the use of the periodic SCM BAND program suite [M. Iliaš and V. Pershina, Inorg. Chem. 61, 15910 (2022)]. Very good agreement is reached between the calculated E_{ads}(TlOH) of 133 kJ/mol on the fully hydroxylated and of 157 kJ/mol on the partially dehydroxylated quartz surfaces on the one hand and experimental adsorption enthalpies, $-\Delta H_{ads}$, of 134/137±5 kJ/mol (at ~300 °C) and 158 ±3 kJ/mol (at ~500 °C), respectively, on the other hand. Taking into account this perfect agreement, we suggest that all the experimental ΔH_{ads} values for Tl should be assigned to the adsorption/desorption of the TlOH molecule. For NhOH, its adsorption properties on various quartz surfaces should be very similar to those of TlOH, with slightly smaller E_{ads} values.

Adsorption properties of group 1 and 2 elements and their compounds including those of elements 119 and 120 on the gold surface were calculated using a periodic BAND suite. According to the results, the elements of both groups should well adsorb on the gold surface, with the weakest adsorption of E119 (E_{ads} of 262 kJ/mol) and E120 (E_{ads} of 185 kJ/mol) caused by the relativistic stabilization of the 8s AO. For group 1 species, the sequence is $E_{ads}(MH) > E_{ads}(M) > E_{ads}(MOH)$.

To assist current gas-phase experiments on the volatility of At, a homolog of tennessine (Ts, element 117), calculations of E_{ads} of At and its compounds on hydroxylated quartz surfaces were performed using the BAND software. It was shown that elemental At should adsorb on the quartz surface very weakly with E_{ads} of -26.3 kJ/mol on geminal and -19.7 kJ/mol on vicinal silanols, while AtOH should adsorb more strongly with E_{ads} of -35.5 kJ/mol on geminal and -41.2 kJ/mol on vicinal silanols.

Selected publications of 2022

- [1] Yakushev, A. ; Lens, L. ; Düllmann, C. E. ; et al.: On the adsorption and reactivity of element 114, flerovium. Frontiers in Chemistry 10, 976635 (2022), DOI:10.3389/fchem.2022.976635
- [2] Pershina, V. ; Ilias, M.: Reactivity of superheavy elements Cn and Fl and of their oxides in comparison with homologous species of Hg and Pb, respectively, towards gold and hydroxylated quartz surfaces. Dalton transactions 51(18), 7321 - 7332 (2022), DOI:10.1039/D2DT00240J
- [3] Khuyagbaatar, J.: Fission-stability of high-K states in superheavy nuclei. The European physical journal / A 58(12), 243 (2022), DOI:10.1140/epja/s10050-022-00896-3
- [4] Warbinek, J. ; Anđelić, B. ; Block, M. ; et al.: Advancing Radiation-Detected Resonance Ionization towards Heavier Elements and More Exotic Nuclides. Atoms 10(2), 41 (2022), DOI:10.3390/atoms10020041
- [5] Kaleja, O. ; Anđelić, B. ; Bezrodnova, O. ; et al.: Direct high-precision mass spectrometry of superheavy elements with SHIPTRAP. Physical review / C 106(5), 054325 (2022), DOI:10.1103/PhysRevC.106.054325
- [6] Münzberg, D. ; Block, M. ; Claessens, A. ; et al.: Resolution Characterizations of JetRIS in Mainz Using 164Dy. Atoms 10(2), 57 (2022), DOI:10.3390/atoms10020057

5. Research of the PANDA Departments

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

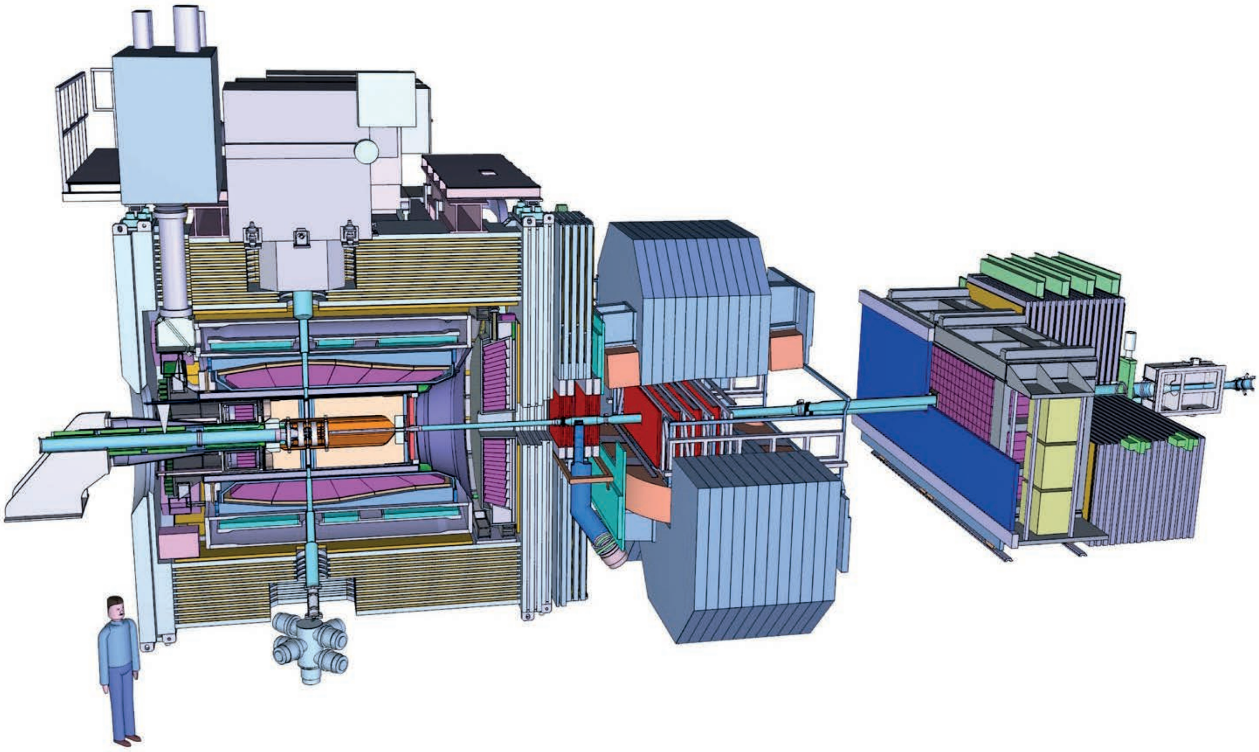

Figure 45. PANDA Detector (Illustration by J. Lühning, GSI)

The PANDA experiment (s. 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-lab 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, the experiment infrastructure and the Gas Electron Multiplier (GEM) detector. This is accompanied by Phase-0 activities like cooperation for the GlueX-DIRC at Jefferson Lab (Newport News, USA) and data analysis at GlueX and BESIII at IHEP (Beijing, VR China). 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.

5.1 Department Hadron Spectroscopy

Head: Prof. Dr. Klaus Peters (GSI & Goethe University Frankfurt)
Authors: Anastasios Belias, Klaus Götzen, Klaus Peters, Lars Schmitt (FAIR)

The Day-1 setup of PANDA which accounts for the available funding, production schedules and the needs of the early physics program, is under full construction. Core systems of the Day-1 setup are the cluster-jet target, the solenoid magnet with the muon system, the Micro Vertex Detector (MVD), the straw tube tracker (STT), the Barrel DIRC and Barrel Time-of-Flight (ToF) Counter, the forward and backward endcaps of the EMC, 12 slices (out of 16) of the Barrel EMC, 2 stations (out of 3) of the GEM detector and 4 (out of 6) stations of the forward tracker, the Forward ToF, the Forward calorimeter and the Luminosity Detector. There is a variety of tasks ongoing in the Hadron Spectroscopy Department for the construction and assembly of the detector as well as its operation and analysis. Progress in magnet assembly, infrastructure and routing, and central mechanical support elements as well as scrutiny of final designs and the follow-up on detector production elsewhere have been accomplished by the PANDA technical coordination team while the software group was focusing on the analysis of FAIR Phase-0 experiments.

Highlights in 2022

PANDA Infrastructure Design Work

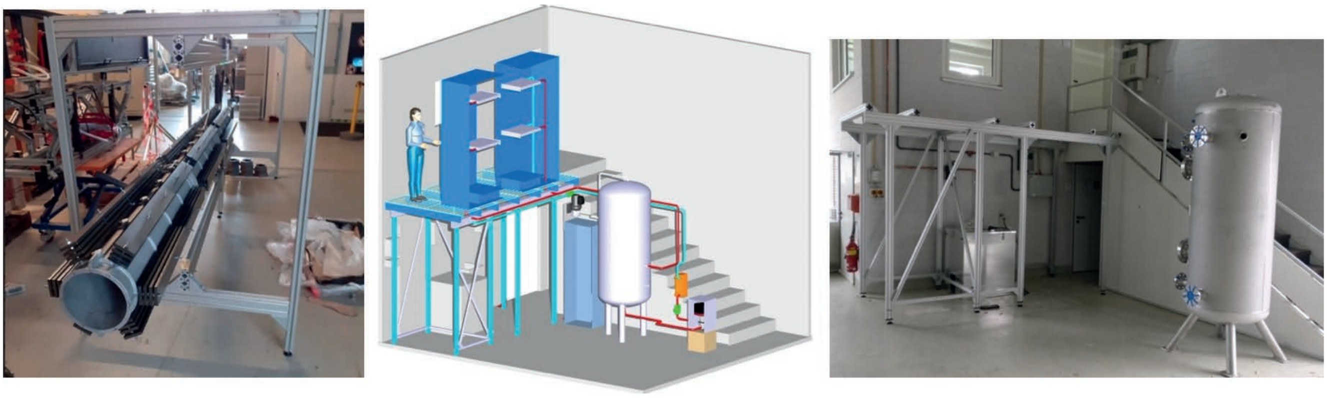

Figure 46. (Left) Load test of CSF. (Middle and Right) Layout of test stand and a test assembly in the Laboratory.

In late 2021 the assembly of the carbon-fibre-based prototype of the PANDA Central Support Frame (CSF), that will hold the beam-target-pipe, the MVD and the STT of PANDA, was completed. In spring 2022 load tests with steel plates of in sum 160 kg mass were successfully performed (see Figure 46 left). The weight represents the expected load on the frame from the services of the MVD system. Further work is done at FZ Jülich to integrate support rings of the STT onto the CSF.

In the framework of the planning of auxiliary structures for the experiment assembly a mounting device was designed capable of inserting the entire Forward Endcap EMC into the solenoid magnet. The device allows precise positioning, lifting and insertion of the detector. With a different holding structure the device can also insert the GEM Tracker.

In the framework of the planning of auxiliary structures for the experiment assembly a mounting device was designed capable of inserting the entire Forward Endcap EMC into the solenoid magnet. The device allows precise positioning, lifting and insertion of the detector. With a different holding structure the device can also insert the GEM Tracker.

A coordinated campaign was started to construct a test stand for the characterization of a cooling system for electronic racks operating at sub-atmospheric pressures to avoid any harmful leakage of cooling water. Operation and control of such a system requires a delicate balance of levels and pumping power and needs to be studied experimentally before being able to design the much larger system required for the 160 electronics racks of the PANDA experiment.

The test stand will consist of a platform to host two electronics racks equipped with heat exchangers, power consumers and ventilation, a reservoir tank and a set of pumps and control units to operate the cooling circuit (see Figure 46 middle). The racks need to be placed at an elevated position with respect to the water reservoir to allow for a natural backflow when pumping is interrupted. Findings of the tests will benefit also other applications of sub-atmospheric cooling systems. The platform was assembled at the end of 2022 and a used reservoir tank was made available (see Figure 46 right). First programs of a control system based on Arduino microcontrollers were developed.

Finally, a study was begun to evaluate the possibilities to produce the thin low-mass PANDA beam-target cross pipe with innovative manufacturing techniques and low-Z materials, investigating carbon fibre materials and 3D printed Aluminum structures.

PANDA use of the LHCb Outer Tracker

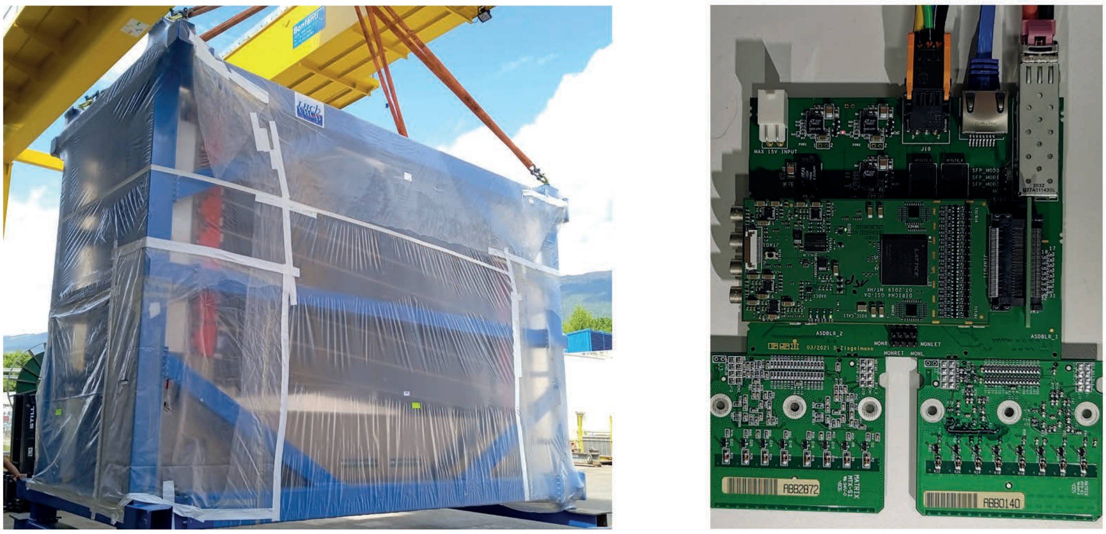

Figure 47. (Left) The whole LHCb OT inside the transport frame prepared at CERN. (Right) GSI Readout board to interface the LHCb OT and PANDA DAQ.

The LHCb Outer Tracker is a gaseous straw tube detector used in the LHCb experiment from 2009 until 2018. The LHC upgrades made this Outer Tracker available for scientific use elsewhere. The PANDA TC group has been in close contact with LHCb to re-use the whole Outer Tracker, all its detector modules and FEE (ASIC), foremost in the PANDA experiment and any other GSI/FAIR activities. In particular, the Outer Tracker is considered as Forward Tracker stations FT5 and FT6, and notably due to the drop-out of the Russian contributions, to provide a Muon Range System, both usable in the PANDA Forward Spectrometer. Design iterations of the layout of the muon forward range system equipped with LHCb OT detectors were studied. Preparations for safe detector handling and transport, including the logistics for storage at CERN and at GSI took place throughout the year with safety, storage, and transport teams at both sites. The legal agreements for the transfer of title to GSI have been signed in Q4/2022, and arrival at GSI is foreseen in Q1/2023 (see Figure 47 left). Anticipating the use of the LHCb Outer Tracker in PANDA, we have developed a readout board to interface the original ASICs to the PANDA DAQ system (see Figure 47 right). Students at GSI participate in this project and first prototypes produced at GSI/EEL are ready for tests in 2023.

PANDA Software Trigger

The efforts for the PANDA Software Trigger supported by machine learning techniques aiming at signal efficiency optimization for a fixed accepted background rate were finalized. In summary a convolutional neural network with four residual blocks with up to 140 input variables applied in a binary classification scheme achieved efficiency gains of up to a factor three (i.e. relative gain of 200%) compared to a conventional cut and count approach. By adding event shape input variables, the data quality could even be improved in addition. The study has just been submitted to EPJC and is already available in arXiv [1].

Following up on this, studies are ongoing concerning a systematic conservation and improvement of data quality for post-trigger analysis. This affects e.g., the flatness of the signal and background efficiencies over the kinematic phase space. Here a mechanism was developed to inject feedback about the flatness in the backpropagation mechanism during neural network training. While further and more comprehensive studies are needed, the first results look very promising.

As a last topic, an alternative triggering approach was investigated, working directly with the detector raw data and digitized data rather than completely reconstructed event candidates. This principal approach would be very beneficial in the given online scenario. Although this method delivers decent performance for channels with rather specific kinematic properties, comprehensive further feasibility studies are needed for a conclusion.

FAIR Phase-0: Analysis of BESIII and GlueX

The analysis of the BESIII data mainly focused on the search for not yet observed decay channels of the exotic candidate ψ(4230). Concretely a search for decays comprising baryons with strangeness in reactions $e^+e^- \rightarrow \Lambda X$ has been carried out and completed. The investigated center-of-mass energy range was 4.13 GeV to 4.44 GeV, and the cross section for the above-mentioned reaction was measured separately for the hyperons and anti-hyperons. The final energy dependent cross section spectrum shows three enhancements, which can be identified with the states ψ(4230), ψ(4360), and ψ(4415), all being observed here for the first time decaying to Λ hyperons. The corresponding PhD thesis has just been submitted [2].

Furthermore, investigations have been started to study the principal possibility of identifying reactions of interest with unsupervised neural networks. For that purpose, clustering techniques have been applied to simplified Monte Carlo simulation based on the BESIII detector properties. The input variables were various multi-particle invariant masses, the input dimension in the order of five to ten. While it is possible to identify clusters with rather high accuracy, it is not yet conclusive whether events with “new physics” can positively be identified. More comprehensive studies are needed in that respect.

The analysis of the search for φ(2170) in reactions $\gamma p \rightarrow \varphi\pi^+\pi^- p$ in three photon scattering data sets recorded between 2017 and 2018 with the GlueX detector has been completely revised, mainly with regards to systematic uncertainty considerations. The production cross section $\sigma(\gamma p \rightarrow \varphi\pi+\pi-p)$ for photon beam energies E_γ between 6.5 GeV and 11.6 GeV is determined to be in the range between 50 nb and 70 nb. The subsequent search for the exotic candidate φ(2170) did not result in a positive signal observation. Thus an upper limit of about 210 pb was derived for the cross section product $\sigma(\gamma p \rightarrow \varphi(2170)p) \cdot B(\varphi(2170) \rightarrow \varphi\pi^+\pi^-)$. The analysis has been submitted to the internal review process within the GlueX collaboration and is planned to be published in the beginning of 2023.

Outlook for 2023

The main objectives for the coming year are:

- Planning for an intermediate hadron physics experiment at GSI.
- Tests of the GSI interface board for the Outer Tracker readout.
- Infrastructure technology developments for cooling and beam pipes.
- New BESIII analysis on X, Y, Z states in e+e- annihilation using ML techniques.
- Completion and publication of GlueX cross section analysis.

Selected publications of 2022

- [1] P. Jiang et al.: Deep Machine Learning for the PANDA Software Trigger, arXiv:2211.15390v1, 2022
- [2] Himmelreich, M.: Inclusive Reconstruction of the Λ^0 Hyperon at Center-of-Mass Energies from 4.13 GeV to 4.44 GeV at BESIII. (2022) Dissertation, Goethe-Universität Frankfurt, 2023

5.2 Department PANDA Detectors

Head: Dr. Jochen Schwiening (GSI)
Authors: Ahmed Ali (HI Mainz), Albert Lehmann (Friedrich-Alexander-Universität Erlangen) & Jochen Schwiening

The main objective of the department is the development and construction of solid-state Ring Imaging Cherenkov Detectors, known as DIRC (Detection of Internally Reflected Cherenkov Light) counters. 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 particles. The group currently participates in the design, construction, and operation of DIRC detectors in three large experiments: PANDA at FAIR, GlueX at the Thomas Jefferson National Accelerator Facility (JLab), USA, and ePIC at the Brookhaven National Laboratory (BNL), USA.

Highlights in 2022

Quality assurance of PANDA Barrel DIRC components, start of DIRC assembly

GSI is the lead group for the PANDA Barrel DIRC detector, a German in-kind contribution to PANDA. The activities are performed in close cooperation with the Universities of Erlangen and Mainz and the HI Mainz. Following the successful conclusion of the fabrication of the fused silica DIRC bars in March 2021 and the start of the series production of the micro-channel plate PMT (MCP-PMT) sensors, with the first lot delivered in May 2022, the activity focus in 2022 was on the quality assurance (QA) measurements of the components. The optical quality of the DIRC bars is being evaluated in the DIRC lab at GSI and key properties of the MCP-PMTs are determined in detailed measurements at Erlangen University. The first prototype of a DIRC bar box, made from carbon-fiber-reinforced polymer (CFRP), was delivered in February 2022. Measurements of the mechanical properties and a long-term study of the possible impact of outgassing from the resin in the CFRP material on the DIRC bar surfaces are underway. A new R&D project was started at HIM to prepare for the gluing of the DIRC bars and the assembly of the future bar boxes. In March 2022 the high-performance DIRC design, a joint effort by GSI, CUA (Catholic University of America, USA), and ODU (Old Dominion University, USA) was selected by the EIC (Electron-Ion Collider) Detector Proposal Advisory Panel as the primary hadronic PID system for the barrel of the future ePIC detector.

Gluing of the PANDA Barrel DIRC radiator bars

The activities in the HI Mainz were focused on the preparation for the gluing of the fused silica bars and lenses, and the future assembly of the DIRC bar boxes in the DIRC lab at the HI Mainz. The 48 radiator bars for the PANDA Barrel DIRC will be arranged in 16 light-tight boxes, surrounding the beam line in a polygonal barrel. Each bar box will contain three synthetic fused silica bars with the dimensions 17 x 53 x 2400 mm^3, placed side-by-side and separated by a small air gap. Each bar will be produced by gluing two shorter bars end-to-end. The method to assemble these bars is based on the successful BaBar DIRC gluing procedures, using the same glue, with important modifications to accommodate the larger cross-section of the PANDA bars. These improvements need to be validated experimentally. For this purpose, an R&D setup has been prepared in the DIRC lab at the HI Mainz to study each step of the process. After mixing the two components of the Epotek 301-2 glue, a vacuum pump removes air bubbles before the glue is applied to the joint using a precision pipette. During the first stage the tests were performed using glass samples available from industry. Different glue component ratios and curing conditions, as well as various gap widths between the glass pieces, were evaluated by comparing the quality of the glue joint in terms of glue uniformity and number of air bubbles. Since the gluing results depend strongly on the quality and the relative alignment of the two surfaces, one of the PANDA Barrel DIRC bars, produced by Nikon Corp., was sliced into 53 mm-wide pieces at MDI Advanced Processing GmbH in Mainz using a laser ablation technique. Figure 48 shows the Nikon bar during the laser procedure (Figure 48 a) and two of the obtained bar samples in the gluing setup (Figure 48 b). The distances between the fused silica samples and the relative alignment can be controlled using micrometers, an optical microscope and an autocollimator, respectively (Figure 48 c). By varying the relative orientation of the samples as well as the environmental conditions (lab temperature and humidity), the optimum conditions for the production phase of the 48 long bars will be studied before the first full-size Nikon bars will be glued in 2023.

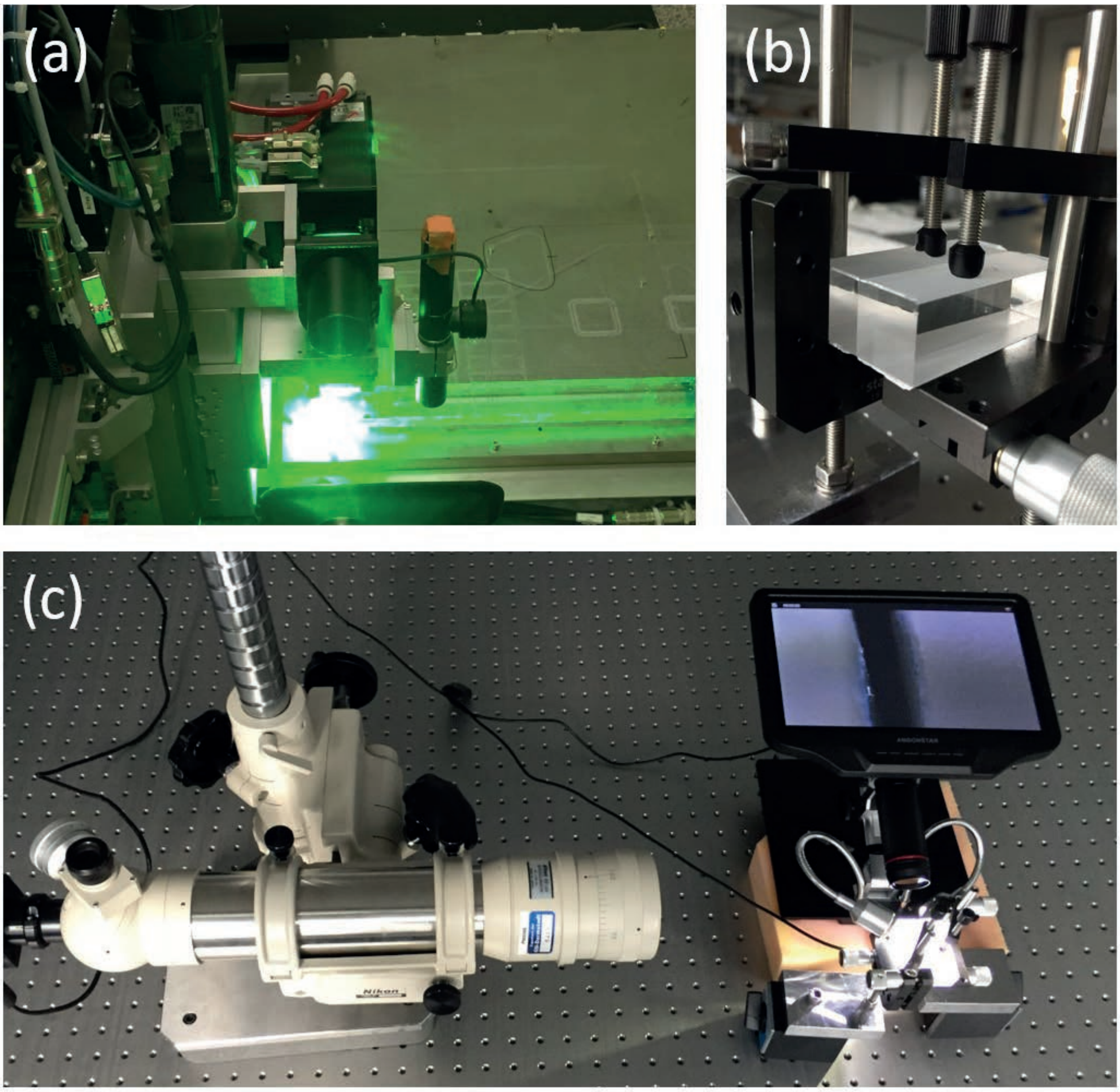

Figure 48. Photos of (a) a DIRC bar during the laser cutting procedure, (b) two fused silica samples in the gluing holder, and (c) the gluing R&D setup in the new DIRC lab at HIM with an autocollimator and optical microscope monitoring the samples. (Photos by A. Ali, HIM)

Evaluation of the MCP-PMTs for the Barrel DIRC

The evaluation and quality control of the microchannel-plate photomultiplier tubes (MCP-PMTs) is performed in Erlangen. Over the last years the suitability of MCP-PMTs as photon detectors for the Barrel DIRC was demonstrated. Among others the most critical performance parameters were proven: a lifetime of at least 5 C/cm^2 integrated anode charge (IAC) in 10 years of PANDA operation (Figure 49 a), a photon rate capability of ~0.5 MHz/cm^2, a gain of at least 10^6 inside a magnetic field of ~1 T (Figure 49 e), and a time resolution of ~100 ps. The 100-fold lifetime increase, compared to MCP-PMTs from before 2011, was reached by coating the MCP pores with ultra-thin layers of alumina and/or magnesia using an atomic layer deposition (ALD) technique.

Throughout 2022 the first of the 155 series production 2-inch MCP-PMTs from Photonis were delivered and evaluated. An important performance criterion is the quantum efficiency (QE) and gain homogeneity across the active surface of the PMT. Example results are shown for a QE xy-scan of one PMT (Figure 49 b) and as maximum/minimum ratio plots of the QE (Figure 49 c) and gain (Figure 49 d) for the 64 anode pixels of five series production PMTs. Unfortunately, some of the PMTs still showed the recently discovered “escalation effect" of ALD-coated PMTs, which, at high gain operation, may lead to photon emission from inside the PMT accompanied by a significant rise in dark count rate and a dropping gain. With regular feedback from Erlangen the producer Photonis was able to optimize their ALD-coating process, which reduces this effect to a tolerable level now. Although there are still a few other issues to be optimized in the further production process, the overall performance of most of the delivered tubes was good. During 2023 we expect a large fraction of the 155 MCP-PMTs to be delivered and evaluated.

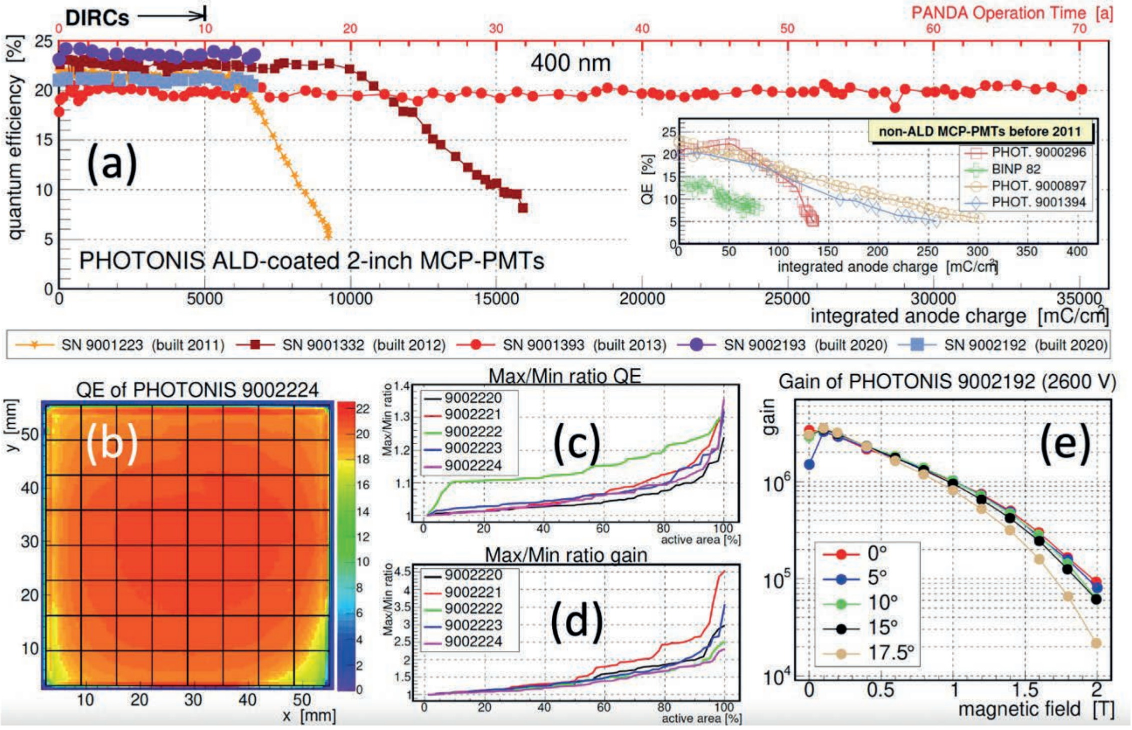

Figure 49. (a) Lifetime of MCP-PMTs: QE vs. IAC at 400 nm of older and recent (9002192, 9002193) ALD-coated Photonis tubes and for previous non-ALD devices (lower right inset). (b) QE homogeneity with the anode pixel grid overlaid. QE (c) and gain (d) max/min ratio of 5 series production PMTs. (e) Gain vs. B-field at different tilt angles between PMT-axis and field direction. (Figures by A. Lehmann, FAU Erlangen)

Outlook for 2023

The series production of PANDA Barrel DIRC MCP-PMTs and the quality assurance measurements will continue in 2023. Based on the outcome of the bar box material test, a near-final design of the bar box prototype will be built and filled with aluminum bars to test the mechanical integrity and installation procedure. A mock-up of the Barrel DIRC readout box is under construction to test different concepts for the time and gain calibration of the MCP-PMTs using a pulsed laser system and to evaluate the recently modified DiRICH readout electronics. The work on the EIC hpDIRC will focus on transporting the legacy DIRC bars from the BaBar experiment from SLAC to Jefferson lab to evaluate the optical quality for a possible reuse in ePIC and on advancing the hpDIRC design to be ready for the Technical Design Report in 2024.

Selected publications of 2022

- [1] Schepers, G. ; Belias, A. ; Dzhygadlo, R. ; et al.: PANDA Barrel DIRC: From Design to Component Production. Journal of physics / Conference series 2374(1), 012119 (2022), DOI:10.1088/1742-6596/2374/1/012119
- [2] Lehmann, A. ; Belias, A. ; Dzhygadlo, R. ; et al.: Latest Technological Advances with MCP-PMTs. Journal of physics / Conference series 2374(1), 012128 (2022), DOI:10.1088/1742-6596/2374/1/012128
- [3] Ali, A. ; Barbosa, F. ; Bessuille, J. ; et al.: Initial performance of the GlueX DIRC detector. Journal of physics / Conference series 2374(1), 012009 (2022), DOI:10.1088/1742-6596/2374/1/012009
- [4] Adam, J. ; Adamczyk, L. ; Agrawal, N. ; et al.: ATHENA detector proposal — a totally hermetic electron nucleus apparatus proposed for IP6 at the Electron-Ion Collider. Journal of Instrumentation 17(10), P10019 (2022), DOI:10.1088/1748-0221/17/10/P10019

6. FFN (FAIR Forschung NRW)

Coordination: Prof. James Ritman (GSI & Ruhr-Universität Bochum)

6.1 Neutrino Physics

Head: Prof. Dr. L. Ludhova (FZ-Jülich, RWTH-Aachen)
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Borexino

The Borexino experiment, that took data from May 2007 until October 2021, featured a 280-ton liquid scintillator (LS) detector with the world's highest radiopurity. In 2022, Borexino presented an improved measurement of the CNO solar neutrino interaction rate obtained with the complete Borexino Phase-III dataset. The measured rate RCNO = $6.7^{+2.0}$ counts/(day · 100 tons) allowed us to exclude the absence of the CNO signal with about 7σ C.L. The new CNO flux measurement was used together with the 8B flux stemming from the global analysis of all solar neutrino data to evaluate the abundance of C and N with respect to H in the Sun with solar neutrinos for the first time. The result displays a ~2σ tension with the "low metallicity" spectroscopic photospheric measurements. The paper describing this result was accepted for publication by PRL and selected as the Editors' suggestion [1].

Borexino developed a new method, called Correlated and Integrated Directionality (CID), that exploits the directional Cherenkov light in LS detector, in order to disentangle the solar neutrino signal, correlated with the known Sun's position, from the isotropic background. In the region of interest, selected such to be dominated by the signal from 0.862 MeV 7Be solar neutrinos, the no-solar neutrino hypothesis was excluded with >5σ [2, 3].

JUNO

The JUNO Experiment is a neutrino experiment under construction near Kaiping city in Southern China, with a planned completion in 2023. The design-driving main goal is the determination of the Neutrino Mass Ordering (NMO) using reactor electron anti-neutrinos from the two strong nuclear power plants at a distance of about 53 km. JUNO has also a broad physics program addressing various topics in neutrino, particle, and astrophysics. To reach its goals, the JUNO detector requires a high level of radiopurity. To ensure this, the 20-ton OSIRIS LS detector will be used to monitor the radio-purity of the LS during its months-long purification and filling into the main JUNO detector. Our group is responsible for the calibration of the OSIRIS detector with radioactive and LED sources. Two PhD students spent a few months periods at the experimental site working on the installation of the OSIRIS detector and preparations for the calibration. In 2022, our group in a close collaboration with the INFN Milano group, finalized the sensitivity study to 7Be, pep, and CNO solar neutrinos. Additionally, we implemented the topological reconstruction method, developed at DESY Hamburg, in JUNO. The main goal is to reconstruct the direction and energy of the fully contained atmospheric neutrino events, a prerequisite to boost the JUNO NMO sensitivity in a combined analysis of reactor and atmospheric neutrinos. The first results towards the directionality reconstruction were presented at the Neutrino conference.

DOI:10.15120/GSI-2023-00462

Outlook for 2023

In Borexino we are currently exploring the possibility to apply the CID method in the measurement of CNO solar neutrinos using the combined Phase 2+3 data set.

The JUNO sensitivity study to ^{7}Be, pep, and CNO solar neutrinos has passed the internal review. The respective collaboration paper is written, will be submitted for the internal collaboration review shortly and is expected to be published in 2023. With the experience from Borexino, we are now studying the CID application in JUNO for the measurement of CNO solar neutrinos. The first results are very encouraging. We plan to further elaborate on this topic and eventually suggest a dedicated calibration procedure for the Cherenkov light and eventually prepare a dedicated publication. We also started the sensitivity study to NMO and geoneutrinos (both detected with the Inverse Beta Decay interaction) using in input the full Monte Carlo chain for all signal and background components. We plan to develop a corresponding fitting procedure and to finalize the topological reconstruction of atmospheric neutrinos. Additionally, we will work on the preparations for the detector commissioning, covering the topics as detector calibration, online event classification, Monte Carlo simulation, event reconstruction, and event data model.

Selected publications of 2022

- [1] Appel, S. ; Bagdasarian, Z. ; Basilico, D. ; et al.: Improved measurement of solar neutrinos from the Carbon-Nitrogen-Oxygen cycle by Borexino and its implications for the Standard Solar Model. Physical review letters 129(25), 252701 (2022), DOI:10.1103/PhysRevLett.129.252701
- [2] Agostini, M. ; Altenmüller, K. ; Appel, S. ; et al.: First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino. Physical review letters 128(9), 091803 (2022), DOI:10.1103/PhysRevLett.128.091803
- [3] Agostini, M. ; Altenmüller, K. ; Appel, S. ; et al.: Correlated and integrated directionality for sub-MeV solar neutrinos in Borexino. Physical review / D 105(5), 052002 (2022), DOI:10.1103/PhysRevD.105.052002
- [4] Abusleme, A. ; Adam, T. ; Ahmad, S. ; et al.: Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO. Chinese physics / C 46(12), 123001 (2022), DOI:10.1088/1674-1137/ac8bc9
- [5] van Waasen, S. ; Genster, C. ; Göttel, A. ; et al.: JUNO physics and detector. Progress in particle and nuclear physics 123, 103927 (2022), DOI:10.1016/j.ppnp.2021.103927

6.2 HADES as FAIR Phase-0 for PANDA

Head: Dr. J. Messchendorp (GSI)
Authors: W. Esmail (GSI), A. Foda (GSI), J. Gollub (RU-Bochum), A. Illari (U. of Connecticut), R. Kliemt (RU-Bochum), J.G. Messchendorp (GSI), S. Pattnaik (GSI, RU-Bochum), G. Perez-Andrade (FZ-Jülich), J. Regina (GSI), J. Ritman (GSI, RU-Bochum), M. Romano U. of Palermo), A. Strach (Jagiellonian University), P. Wintz (FZ-Jülich)

We are exploring the production mechanisms and spectroscopy of baryons with strangeness contents, i.e. hyperons, using the SIS18 beam at HADES, which is an excellent facility to study hyperons in proton-proton and pion-proton scattering. Recently, HADES has been upgraded with a forward detector composed of straw-tube trackers (STS1/STS2) and a forward RPC (fRPC), which significantly improve the acceptance for hyperons. Furthermore, a trigger scintillator (iTOF) consisting of 6 plastic scintillating modules with SiPM readout, covering the first MDC plane was added. In February and March, HADES collected 4 weeks of data on hyperon production in proton-proton scattering using a T=4.5 GeV beam impinging on a 5 cm liquid hydrogen target. This experiment builds on our previous studies at 3.5 GeV [1,2]. In addition to the hardware operation and calibration reported elsewhere, we are concentrating on the alignment and track reconstruction of the forward detector as well as analyzing exclusive events.

The forward Straw Tracking Stations were commissioned in 2021 and successfully used for the production beamtime in 2022. A tracking procedure is under development that optimizes the efficiency. Currently straight lines are fit to the two tracking stations, and now a new procedure that performs the hit clusterization in both stations simultaneously is being tested and optimized. Two alignment procedures were developed and tested. Both are based on selecting proton-proton elastic scattering events with one proton in the main HADES detector and one in the forward detector. The first was implemented by a summer student and is based on artificial neural networks with fully connected, dense layers. By providing residuals (closest distance between the hit tubes and tracks) as a loss function, the network was able to predict misalignment of straw layers. The other approach exploits the good angular resolution of the main HADES detector to estimate the expected reconstructed angles of the forward-going proton. This method gives promising preliminary results and and is currently being optimized.

Elastic scattering events were selected and analyzed to estimate the overall integrated luminosity reached during the production run with the upgraded HADES including the forward detector. The analysis focused on the selection of elastically scattered protons whereby one of the protons was reconstructed in the forward detector in coincidence with the other registered by the main HADES. By exploiting the kinematical topology of the two-body reaction, an unambiguous identification of the elastic scattering process can be obtained resulting in an estimate of the total integrated luminosity of about 5.9 pb^{-1}, compatible with complementary studies performed by others in the collaboration.

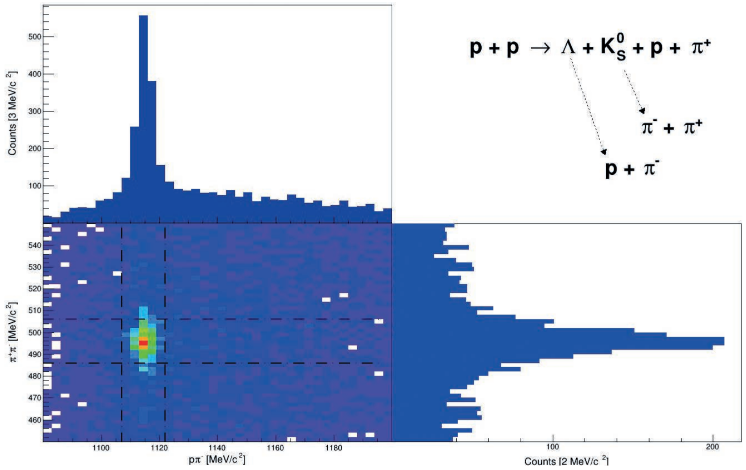

Figure 50. Preliminary reconstructed invariant mass distribution of the π^+ π- versus the $p\pi^-$ final state. The data were obtained during the recent beam time using a 4.5 GeV proton beam on a liquid-hydrogen target. Events were selected based on their fully reconstructed final state of the strangeness-production reaction given in the right-top panel.

A kinematic fitting library based on Lagrange multipliers and utilizing different constraints, e.g., geometrical vertex or momentum conservation at a decay vertex has been implemented as an external library for HYDRA, the HADES software package. The fitting algorithms have been successfully tested using toy MC data including topologies involving complex hyperon decays. Part of that work was done by a summer student. A geometrical vertex fit was applied to the $p\pi^+\Lambda K^0_S$ channel and the inclusive Λ reconstruction efficiency was found to be about 30%.

A particle identification (PID) algorithm has been developed to select a high purity sample of particle species as required in the data analysis. The conventional approach used in HADES is to apply so-called "graphical cuts" around the theoretical Bethe-Bloch curves. This approach is justified when the separation between various particle species is significantly large. However, this is no longer optimal when the distributions associated with the particle species begin to overlap. An alternative approach is to utilize deep learning algorithms. The developed neural network algorithm has been trained in a semi-supervised way simultaneously on simulated and real data to accommodate for the discrepancies between the two data domains (simulated data and unlabeled experimental data). With Domain Adversarial Neural Networks (DANN) we have significantly improved the classification of particle species in the experimental data.

Figure 50 depicts preliminary results of an exclusive analysis of the $p+p \to \Lambda(\to \pi^- p)+K_S(\to \pi^+ \pi^-)+\pi^+ + p$ reaction channel. The data, recently taken with a proton beam of 4.5 GeV, correspond to about one day of beam time. The PID exploits the relative time-of-flight of the various final state particles with respect to the π^- from the Λ decay. Moreover, vertex and momentum constraints have been applied to improve the signal to background ratio and to be selective to long-lived hyperon decays. A data-driven analysis procedure was developed to optimize the Lambda identification. Note the clear coincidence between reconstructed Λ and K_S decays, thus demonstrating the excellent capabilities of HADES to perform an exclusive analysis of a reaction including hyperons.

Outlook for 2023

In the upcoming year we will continue to harvest results from the 4.5 GeV proton-proton data, with our focus primarily on event selection to obtain (preliminary) cross sections of exclusive channels involving the production of hyperons. Moreover, preparatory studies will be pursued in view of the foreseen pion beam a part of the FAIR Phase Zero. A prospective study of the physics potential of pion-beam time is underway. The study utilizes partial-wave analysis techniques implemented in the Bonn-Gatchina framework to demonstrate the predictive power of HADES for resonance studies in the two-pion final state. Also, we plan to build a partial-wave analysis framework specific to HADES in preparation to future spectroscopy studies. One central theme of our activities is the usage of machine learning methods in the event selection and physics analysis. The ambition is to enrich these activities by deploying artificial intelligence (AI) techniques on the level of the experiment control. This is strongly motivated by the foreseen requirements in the operation of FAIR experiments such as PANDA and CBM. These future facilities will need to cope with a significantly higher complexity in data handling, hence, requiring a paradigm shift on several levels including the control of detectors during data taking. The HADES, FAIR Phase0, experiment is ideally suited as a prototype environment to evaluate and develop an AI-based smart sensor control. In the context of a recently started NRW-FAIR network, a work package will begin in 2023.

Selected publications of 2022

- [1] Esmail, W. A. M.: Deep Learning for Track Finding and the Reconstruction of Excited Hyperons in Proton Induced Reactions. Ruhr-Universität Bochum 182 p. (2021) [10.13154/294-8563] = Dissertation, Ruhr-Universität Bochum, 2021
- [2] Esmail, W. A. M. ; HADES Collaboration: Investigation of the Σ 0 hyperon production in p(3.5GeV)+p collisions. The European physical journal / Web of Conferences 271, 08013 (2022), DOI:10.1051/epjconf/202227108013

6.3 PANDA

Head: Prof. J. Ritman (GSI, Ruhr-Uni-Bochum)
Authors: G. Perez-Andrade (FZ-Jülich), Tobias Stockmanns (FZ-Jülich), Peter Wintz (FZ-Jülich), Huagen Xu (FZ-Jülich)

Software

One of the main challenges in the analysis of the detector data from the PANDA experiment is the search for charged particle tracks in the sum of all hit points measured by the tracking detectors of the experiment. The 3D hit points of the Micro Vertex Detector (MVD) and the GEM Detector have to be combined with the 2D and time information of the Straw Tube Tracker (STT).

Many algorithms have been developed in the PANDA collaboration but all of them assume, that the particles are coming from the known primary interaction point. For most of the physics cases this is a valid assumption but not for all. Therefore, a dedicated track finder for secondary particles is needed. The difficulty for such an algorithm is that the number of possible combinations rises significantly and an anchor point for the tracking is missing if the primary interaction point is not used.

Already in the last year an algorithm based on selecting triplets of hits in the Straw Tube Tracker and combining them into full track candidates to find tracks from secondary particles was presented and showed very good efficiencies. This algorithm was further optimized this year and its performance tested on a simulated interaction of an antiproton beam with a proton target where two cascade particles are created. One of the cascade particles is in an excited state and immediately decays into a stable charged kaon and a long living lambda particle, which further decays after a few centimeters flight path into a stable proton and pion. The ground state cascade decay after a few centimeters flight into a pion and a lambda, which further decays. In summary this decay chain contains six stable charged particles all originating from decay points several centimeters away from the primary interaction point.

This makes this channel very difficult to analyze with the existing primary track finders and an ideal case for the newly developed secondary track finder. By combining a primary track finder for tracks coming from close to the interaction point and the new secondary track finder, the reconstruction efficiency could be improved by more than a factor 3 compared with the result for the primary track finder only. This result shows the quality of the secondary track finder. The next stages in the development are an optimization at which stage the secondary track finder takes over from the primary track finder. Another approach is followed for a second algorithm based on a language model. The language model is a statistical model that assigns probabilities to the patterns recorded based on their frequencies in the testing samples. Like predicting the next word in a sentence, the next track point is predicted by the sequence of hits already added to the track. This algorithm uses simulated hits in the STT to build the statistical model based on the Monte Carlo truth value and is evaluated on data without the truth information. First results look already very promising but still need some optimization to improve the track finding efficiency.

STT

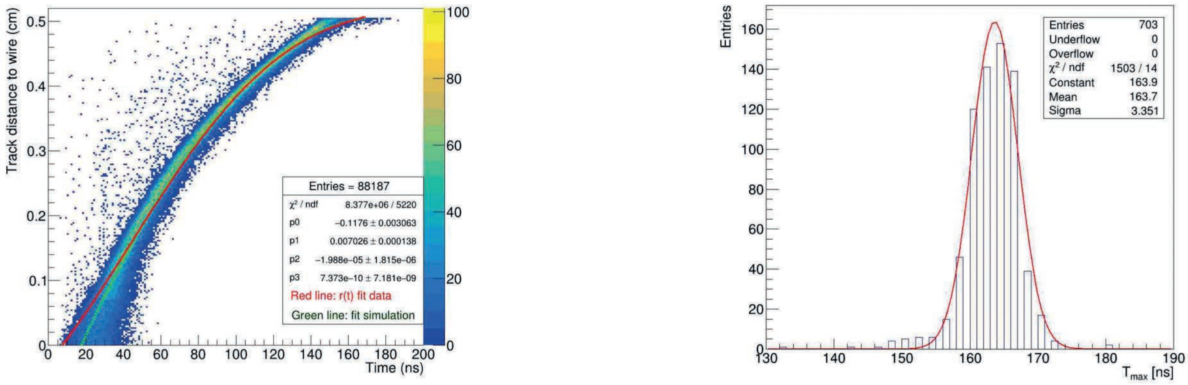

Figure 51. Left: Drift time simulation (Garfield) of proton tracks passing through a single straw and r(t) parametrization (green line: fit to simulation, red line: r(t) calibration for the in-beam data). Right: Distribution of the maximum drift time for all STS1 straws.

The phase 0 experiment beam time to study hyperon production with the new, PANDA-type Straw Stations (STS) in the HADES spectrometer was successfully executed from February to March. No failures of the STS detectors during the four weeks proton beam time were observed and no changes in the settings of the detector or frontend electronics were necessary. This result verifies the various quality assurance methods and measurements during the preparation and set up of the systems, which will be adopted for the PANDA STT.

The calibration methods of the STS for the beamtime data were developed and the calibration of the space – drift time relation for the beam time data has been completed. Figure 51 shows as an example the result of the parametrized isochrones radius - drift time relation r(t) (red line) and the comparison with a simulation of ionizing proton tracks through a single straw (green line: fit of the track distance vs drift time points). As expected, close to the wire the measurement of small track distances is distorted by the varying and Poisson-distributed distances of the ionization clusters along the track path, which limits the resolution in this region. Above about 0.6 mm distance the agreement between the simulated drift motion and r(t) calibration of the data is very good.

Part of the calibration is the determination of the maximum drift time of a straw, which in the end contains all measurement smearing effects and systematic errors, from the straw geometry, electronic readout up to the calibration and r(t) parametrization. The obtained spread of 3.4 ns (σ) for all straws in the STS1 together corresponds to a difference in the straw radius of less than 40 μm, which shows the precise geometry of the PANDA-type straw technology with self-supporting, pressurized and thin-wall film tubes.

KOALA

The KOALA experiment will provide the normalization needed for PANDA to measure its luminosity via antiproton-proton elastic scattering. Several commissioning experiments have been performed with proton beam at COSY, since both reactions have the same kinematics. These tests indicate which limitations exist for KOALA&PANDA to achieve the desired absolute precision. The main effects are from the finite size of the cluster jet target as well as imperfection of the beam alignment.

The focus of KOALA is now to investigate such constraints by software studies. Based on the FairSoft and FairRoot the so-called KoalaSoft has been developed for the simulations as well as the data analysis. In order to fulfill the investigations for the beam and target impacts on the experiment precision the simulation chain for the proton-proton elastic scattering has been implemented. It can be used to generate proton-proton elastic events and reconstruct the t-distribution for further studies.

Outlook for 2023

The next step for the STT system will be to set-up of one hexagon sector with connected readout electronics and test of the system performance.

In the upcoming year more features for the KoalaSoft will be developed. The impacts from a thick target or a poor vacuum performance in the scattering chamber will be investigated. Furthermore, the existing proton-proton elastic scattering data taken at COSY will be analyzed with the KoalaSoft framework.

Selected publications of 2022

- [1] Pérez Andrade, G. ; Lalik, R. ; Ritman, J. ; et al.: Hyperon physics at HADES as a fair phase-0 experiment. Suplemento de la revista mexicana de física 3(3), (2022), DOI:10.31349/SuplRevMexFis.3.0308026
- [2] Malige, A. ; Korcyl, G. ; Firlej, M. ; et al.: Real-Time Data Processing Pipeline for Trigger Readout Board-Based Data Acquisition Systems. IEEE transactions on nuclear science 69(7), 1765 - 1772 (2022), DOI:10.1109/TNS.2022.3186157

6.4 JEDI

Head: Prof. J. Pretz (FZ-Jülich, RWTH-Aachen)
Authors: Andro Kacharava (FZ-Jülich), Jörg Pretz (FZ-Jülich, RWTH-Aachen)

Axion Searches

A paper on the search for axion/axion like particle (ALPs) in a storage ring was published by the JEDI collaboration as a preprint [1] and submitted to a journal. Axions/ALPs introduce an oscillating electric dipole moment (EDM) causing a spin rotation around a radial axis in the storage ring. The so-called axion wind effect causes a pseudomagnetic field resulting in a rotation around the longitudinal axis. Both effects were studied at COSY for the first time. Storage ring experiments are specifically sensitive to the second effect mentioned above (axion wind). No axion/ALP signal was found. Upper limits on several coupling constants were derived from our data. Although planned as an engineering run, in only four days of beam time dedicated to axion searches, we could already set limits on various coupling constants comparable in sensitivity to other experiments.

Investigation of proton spin coherence time

After a successfully reaching over 1000s spin coherence time for deuterons, a first data taking period to investigate the spin coherence time of protons was performed in February 2022 at COSY. Due the fact that the G factor of the proton is an order of magnitude larger compared to the deuteron, is is more difficult to obtain large SCT for protons. The data taking period just served as a first exploratory study where many problems were identified and triggered further investigations.

Electric Dipole Moment (EDM) Searches

The analysis of data on a first measurement of the electric dipole moment of the deuteron is ongoing. The EDM is proportional to a build-up of a vertical build-up of the polarization vector. Systematic effects like magnet misalignments cause vertical build-ups orders of magnitude larger than expected from the EDM. Data analysis [2] and spin tracking simulations [3] are performed to understand these systematic effects in more detail. This include also analysis work on the so-called pilot bunch data, where we demonstrated that we are able to spin-manipulate one bunch in COSY while leaving a second bunch stored simultaneously untouched.

Design Study of a dedicated EDM ring

A proposal "Pathfinder Facility for a new class of PREcision STOrage rings (PRESTO)" was submitted as a "Reseach Infrastructure Concept Development" to the European Commission. A decision on funding is still pending. The PRESTO project aims to work out a detailed Conceptual Design Report (CDR) for a prototype storage ring to perform EDM measurements for protons.

Experiments with polarized beams and targets at the GSI/FAIR storage rings

A Letter of in Intend entitled "Towards experiments with polarized beams and targets at the GSI/FAIR storage rings"

has been submitted to GPAC. The committee encouraged the authors to submit a full proposal. Among the physics topics proposed are axion/ALP searches and the measurement of parity even time reversal odd analyzing power in polarized proton tensor polarized deuteron scattering.

Outlook for 2023

The main goal for 2023 is the finalization of the analysis of the deuteron EDM measurement at COSY, the continuation of the design for a dedicated EDM storage ring and the preparation of a full proposal for experiments with polarized beams and targets at GSI/FAIR storage rings.

Selected publications of 2022

- [1] Karanth, S. ; Stephenson, E. J. ; Chang, S. P. ; et al.: First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam. arXiv (2022), DOI:10.48550/ARXIV.2208.07293
- [2] Andres, A.: The Search for Electric Dipole Moments of Charged Particles in Storage Rings. arXiv (2022), DOI:10.48550/ARXIV.2207.02083
- [3] Vitz, M.: Spin-Tracking Simulations in a COSY Model using Bmad, IPAC22. doi:10.18429/JACoW-IPAC2022-WEPOTK040

6.5 Polarized Atomic Beams

Head: Dr. R. Engels (FZ-Jülich)

A single-pulse radio-wave LASER

When a beam of particles is sent through a sinusoidal, but static magnetic field of two opposing solenoids the particles experience in their system at rest an incoming electromagnetic wave. The corresponding photons are monochromatic, coherent and their frequency can be manipulated either by changing the non-relativistic velocity of the particles or the distance of the coils. Thus, in the inertial system of the particles the solenoidal electromagnetic field acts like a single-pulse radio-wave LASER that can induce magnetic dipole transitions within the hyperfine substates. The photon energies can be chosen between $E_0 \sim 10^{-8}$ and 10^{-12} eV and the corresponding oscillations of the occupation numbers can be simulated due to first-order perturbation theory. This method can be used for any kind of particles with a hyperfine structure (atoms, molecules and their ions).

Precision Spectroscopy

One option to use this technique is to measure the energy splitting of the Zeeman substates of atoms and molecules, e.g., of metastable and ground-state hydrogen and deuterium atoms. A first classical analysis of the observed spectra in a proof-of-principle experiment delivered an energy resolution of about 10^{-11} eV that is limited by the interference of different transitions during the measurement. A Hartree-Fock-like analysis with the use of supercomputer can make use of these interferences and might allow a relative uncertainty down to $\Delta E/E_0 \sim 10^{-5}$ for a single measurement. Long term measurements showed a relative stability of 10^{-4} at least. Thus, it will be possible to measure the QED corrections on the g-factors of the bound electron and the hyperfine-splitting energy of hydrogen and deuterium with a new level of precision. In principle, this method can be used for a beam of anti-hydrogen atoms too.

Outlook for 2023

The interference of the transitions allows a radio-wave induced "pumping" between the Zeeman substates. Thus, this new method opens the door for several other applications.

Polarized sources:

As simpler the hyperfine structure is, as more efficient this effect can be used to polarize the particles passing through the oscillating magnetic field. Meanwhile, this idea was successfully tested for metastable hydrogen atoms, but simulations show that it can be extended for ground-state H(D) atoms, $H_2^+(D_2^+)$- and $H_3^+(D_3^+)$-ions and $H_2(D_2$, HD) molecules and maybe H_2O^+-ions with the existing apparatus to measure the proton and deuteron polarization. Of course, many other ions are possible and in parallel a polarized $^3He^+$ beam can be produced and tested by injection into the cyclotron JULIC. After acceleration the polarization can be measured due to the known analyzing powers of the elastic scattering of unpolarized protons on a polarized ^3He target.

Further outlook:

Further applications might be the production of polarized fuel (D, T, ^3He) for coming fusion reactors or polarized tracer for a better resolution of MRI scans in medicine.

Selected publications of 2022

- [1] Kannis, C.: Theoretical and Experimental Investigation of Sona Transitions. 130 pp. (2023) = Dissertation, RWTH Aachen University, 2023

6.6 Detector Laboratory

Authors: Thomas Krings (FZ-Jülich), Anton Kononov (GSI)

Compton polarimetry is a tool for studying dynamic atomic processes in the relativistic HCI regime which is part of the scientific program of SPARC at FAIR and GSI as well as external experiment facilities like Petra3 at DESY. Furthermore, these experimental technologies allow to look deep into the pure quantum mechanical processes of Rayleigh scattering (commonly well known in the lower “few-keV” region) or Delbrück scattering, both at high x-ray energies. Advanced detector and system development will lead to improved sensitivity and accuracy in the data as well as an enhanced energy range. Together with the atomic physics division at GSI and HI-Jena we are building a Compton telescope system by upgrading an existing planar 2D-Si(Li)-detector system with an additional planar 2D-Ge detector layer.

Outlook for 2023

The main focus of our work will rest on the completion of the upgraded Compton telescope and the final test of all 128 detector elements. Test measurements will be performed together with the atomic physics division at GSI and HI Jena.

The quality of a Compton polarimetry measurement depends on the quality of the detected event histories. The observables are (2D/3D)-position of the events in the crystal, time and spectroscopic energy resolution. Therefore, the improvement of the readout-electronics, especially of the charge-sensitive preamplifiers, is an ongoing process and the integration in already existing detector systems will be one of our tasks in the near future.

In addition to the above-mentioned work, it is planned to move the existing Detector Lab to GSI. A possible collaboration between several groups at GSI is planned to set up an infrastructure to be able to produce Germanium- and Si(Li)-detectors as we have done in Jülich so far.

6.7 Electronics Laboratory

Head: Dr. T. Sefzick (FZ-Jülich)
Authors: Thomas Sefzick (FZ-Jülich), Tanja Hahnraths-von der Gracht (FZ-Jülich), Claudia Berchem (FZ-Jülich), Stephan Kistemann (FZ-Jülich)

The Electronics Laboratory worked on several topics:

- Development and prototype construction of high voltage boards for PANDA STT
- Setup of a control system for the ion source for polarized atomic beams
- Development and production of SiPM boards for the new iTOF detector in HADES
- Cabling and test of stepping motor drive units of the HESR scrapers
- Assembly and test of fan-out modules for beam diagnostics at GSI/FAIR (ongoing)

Outlook for 2023

The main tasks of our work will be the finalization of the assembly of fan-out modules for BEA (Beam Diagnostics), the purchasing, assembly, and testing of Beam Position Monitor (BPM) pre-amplifiers for beam diagnostics, and the increasing support of the GSI experiment electronics division.

Selected publications of 2022

- [1] Grzonka, D. ; Bergmann, P. ; Hahnraths von der Gracht, T. ; et al.: A large area efficient trigger scintillator with SiPM read out. Nuclear instruments & methods in physics research / A 1041, 167410 (2022), DOI:10.1016/j.nima.2022.167410

7. Research of the Theory Departments

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

Theoretical studies are mandatory for the interpretation and understanding of the experimental measurements. On the one hand theoretical predictions allow for experimental tests of fundamental concepts. On the other hand, the interpretation of complex measurements is rarely possible without theoretical analysis. Therefore, the theory groups at GSI work closely together with their experimental colleagues. The theory group of GSI contains from 3 theory departments, i.e. “Nuclear astrophysics and structure” (Head G. Martínez-Pinedo), “Hadron physics and QCD” (Head M. Lutz) and “Hot and dense QCD matter” (Head H. Elfner). These three departments together form now the 5th research pillar of GSI “Theory”.

The European Union has awarded an ERC Synergy Grant to the HEAVYMETAL research project whose principal investigators are Andres Bauswein (GSI Nuclear Astrophysics and Structure department), Darach Watson (University of Copenhagen, Denmark), Padraig Dunne (University College Dublin, Ireland), and Stuart Sim (Queen's University, Belfast, UK). Hannah Elfner has been appointed Senior Fellow at the Frankfurt Institute for Advanced Studies (FIAS).

7.1 Hot and Dense QCD Matter

Head: Prof. Dr. Hannah Elfner (GSI & Goethe University Frankfurt)
Authors: Elena Bratkovskaya, Hannah Elfner

The main goal of the theory group ‘Hot and Dense QCD Matter’ is a dynamical description of heavy-ion collisions at relativistic energies based on kinetic theory, many-body theory and quantum chromodynamics. The complexity of the physical system - created in heavy-ion collisions - requires the development of comprehensive transport approaches in order to explore the possible interpretations of experimental observations within theoretical uncertainties, i.e. - ‘hybrid’ models – combining a macroscopic description of the QGP phase in terms of ‘fluid dynamics’ based on hydrodynamical models and a microscopic description of the hadronic phase - based on mean-field semi-classical BUU type dynamics as in SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) and on quantum-molecular dynamics as in UrQMD (ultra-relativistic Quantum Molecular Dynamics); - microscopic transport approaches - providing a fully microscopic description of hadronic and partonic phases as realized in the off-shell PHSD (Parton-Hadron-String Dynamics) approach for the description of the dynamics of strongly interacting QCD matter based on Kadanoff-Baym equations as well as the PHQMD (Parton-Hadron-Quantum- Molecular Dynamics) – a QMD version of the PHSD. The transport approaches allow to interpret the experimental data as well as to predict physical phenomena for experimental investigation and verification.

Highlights in 2022

Cluster and hypernuclei formation in heavy-ion collisions

The production of clusters and hypernuclei has been studied employing the PHQMD approach, a microscopic n-body transport model based on the QMD propagation of the baryonic degrees of freedom with density dependent 2-body potential interactions [1]. In PHQMD the cluster formation occurs dynamically, caused by the interactions. The clusters are recognized by the Minimum Spanning Tree (MST) algorithm. We present the PHQMD results for cluster and hypernuclei formation in comparison with the available experimental data from SIS to RHIC energies – cf. Fig. 1 (left, middle). We also provide predictions on cluster production for the upcoming FAIR experiments.

PHQMD allows to study the time evolution of the formed clusters and the origin of their production, which helps to understand how such weakly bound objects are formed and survive in the rather dense and hot environment created in heavy-ion collisions. It offers therefore an explanation of the 'ice in the fire' puzzle. To investigate whether this explanation of the 'ice in the fire' puzzle applied only to the MST results we studied also the deuteron production by coalescence. While the coalescence mechanism combines nucleons into deuterons at the kinetic freeze-out hypersurface, the MST identifies the clusters during the different stages of the time evolution. We embed MST and the coalescence prescription in the PHQMD and UrQMD transport approaches in order to obtain model independent results [2]. We have found that both clustering procedures give very similar results for deuteron observables in the UrQMD as well as in the PHQMD environment. This confirms that our solution for the 'ice in the fire' puzzle is common to MST and the coalescence model and independent of the transport approach and related to the fact that the coordinate space distribution of the produced deuterons differs from that of the free nucleons and other hadrons – cf. Fig. 1 (right). The coalescence as well as the MST procedure show that the deuterons remain in transverse direction closer to the center of the heavy-ion collision than free nucleons, i.e. they are spatially separated, which might explain why they are not destroyed by collisions with the hot fireball hadrons.

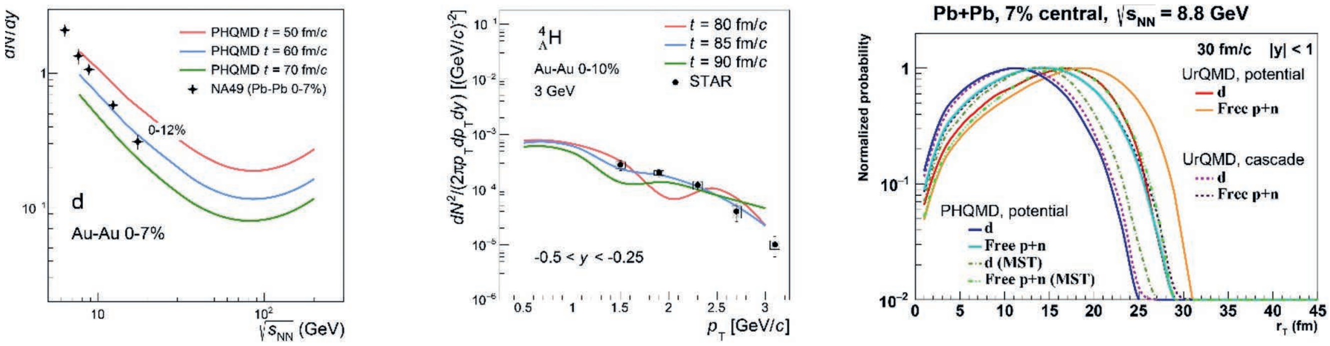

Figure 52. Left: The midrapidity excitation function of dN/dy of deuterons from the PHQMD at times t=50, 60, 70 fm/c as a function of $\sqrt{s_{NN}}$ for central Au+Au collisions in comparison to the data from the NA49 Collaboration [1]. Middle: Transverse momentum distribution of ${}^{4}_{\Lambda}H$ from the PHQMD at times t=80, 85, 90 fm/c for $-0.5<y<-0.25$ for central Au+Au collisions at √sNN = 3 GeV versus experimental data from the STAR Collaboration [1]. Right: Transverse distance of unbound nucleons (p+n) and deuterons from central Pb+Pb collisions for $|y|<1$ at $\sqrt{s_{NN}}$ = 8.8 GeV at 30 fm/c. The solid red line shows the deuterons from UrQMD (potential mode), the solid orange line the free p+n from UrQMD (potential mode), the dashed magenta line represents deuterons from UrQMD (cascade mode), the dashed purple line the free p+n from UrQMD (cascade mode), the blue solid line shows the deuterons from PHQMD (potential mode), and the cyan solid line the free p+n from PHQMD (potential mode). The dark green dot-dashed line shows PHQMD deuterons found by the MST algorithm and the light green dot-dot-dashed line represents free p+n from PHQMD with MST algorithm [2].

Temperature and net baryochemical potential dependence of η/s in a hybrid approach

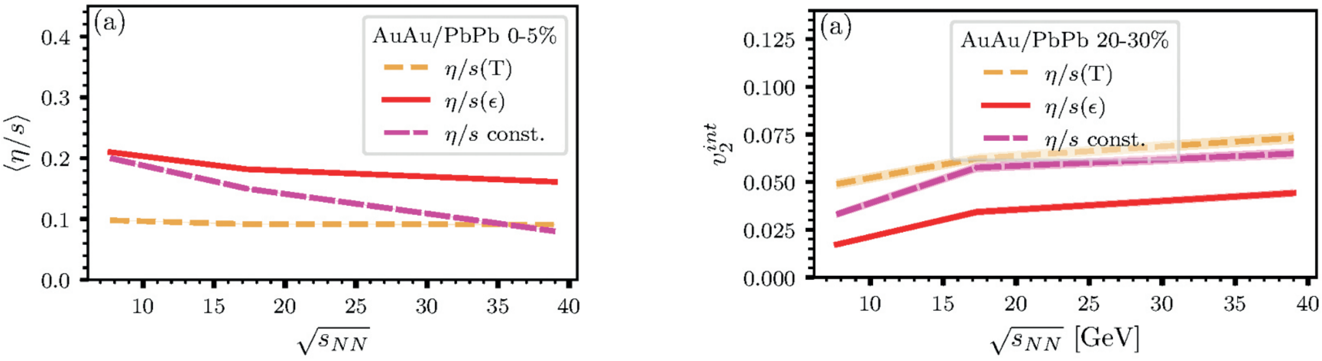

Figure 53. Left: Energy-density weighted mean shear viscosity over entropy ratio <η/s> for central Au+Au/Pb+Pb collisions versus $\sqrt{s_{NN}}$ throughout the hydrodynamic evolution. Comparison between different parametrization choices of η/s are shown by color lines. Right: Integrated event plane elliptic flow of charged hadrons at midrapidity ($|y| < 0.5$) for different parametrization strategies (from left plot) for ε_{switch} decreased to 0.1 GeV/fm³.

The effect of a predicted nonconstant ratio of shear viscosity over entropy density $\eta/s(\mu_B)$ is largely unexplored in hydrodynamic simulations. While previous studies focused only on a temperature dependence or even only a constant effective shear viscosity, in Ref. [3] we have studied the qualitative impact of the net baryochemical potential dependence of the shear viscosity to entropy density ratio η/s in hydrodynamical simulations. The effect of a generalized $\eta/s(T,\mu_B)$ has been investigated in the hybrid approach SMASH-vHLLE, composed of the hadronic transport approach SMASH and the (3+1)-dimensional viscous hydrodynamic code vHLLE [4]. In order to reduce the bias of the result on the equation of state used in the hydrodynamic part of the model, η/s is parametrized directly in the energy density and net baryon number density – cf. Figure 53 (left). The parametrization takes into account the constraints of matching to the transport coefficients in the hadronic phase, as well as perturbative QCD results.

Our work demonstrated an impact of the density dependence for different system sizes and energies and compares the observables, including yield, mean transverse momentum, and integrated elliptic flow (cf. Figure 53 right), with experimental results in the region $\sqrt{s_{NN}}$=7.7–39.0 GeV of the Beam Energy Scan program at the Relativistic Heavy Ion Collider, as the effect of this generalization is especially relevant for intermediate collision energies, for which the system is in equilibrium for a relevant amount of time, but the net baryochemical potential does not vanish. Thus, the effect of an explicit net baryon number dependence on the elliptic flow is negligible and only relevant in the early stages of the collision. Additionally, we found that the proposed parametrization in energy density could be a good proxy for the shear viscosity in the nonequilibrium hadronic transport stage, as the elliptic flow is insensitive to the switching criterion in the range of ε_{switch}=0.1–0.5GeV/fm^3.

Outlook for 2023

In 2023 we will continue to study the QCD matter formed in heavy-ion collisions at FAIR energies within the transport approaches. We will work on an improvement of the understanding of mechanisms of cluster and hypernuclei formation as well as on the study of hadronic and electromagnetic observables which can provide information on the phase transition from hadronic to partonic matter. In the Fall of 2023, a second retreat of the Helmholtz Research Academy Hesse for FAIR is planned to allow for in-depth discussions and synergies with the partners at the other universities.

Selected publications of 2022

- [1] Gläßel, S. ; Kireyeu, V. ; Voronyuk, V. ; et al.: Cluster and hypercluster production in relativistic heavy-ion collisions within the parton-hadron-quantum-molecular-dynamics approach. Physical review / C 105(1), 014908 (2022), DOI:10.1103/PhysRevC.105.014908
- [2] Kireyeu, V. ; Steinheimer, J. ; Aichelin, J. ; et al.: Deuteron production in ultrarelativistic heavy-ion collisions: A comparison of the coalescence and the minimum spanning tree procedure. Physical review / C 105(4), 044909 (2022), DOI:10.1103/PhysRevC.105.044909
- [3] Götz, N. ; Elfner, H.: Temperature and net baryochemical potential dependence of η/s in a hybrid approach. Physical review / C 106(5), 054904 (2022), DOI:10.1103/PhysRevC.106.054904
- [4] Schäfer, A. ; Karpenko, I. ; Wu, X.-Y. ; et al.:Particle production in a hybrid approach for a beam energy scan of Au+Au/Pb+Pb collisions between $\sqrt{s_{NN}}$ = 4.3 GeV and $\sqrt{s_{NN}}$ = 200.0 GeV. The European physical journal / A 58(11), 230 (2022), DOI:10.1140/epja/s10050-022-00872-x

7.2 Nuclear Astrophysics and Structure

Head: Prof. Dr. Gabriel Martínez-Pinedo (GSI & Technische Universität Darmstadt)
Authors: Andreas Bauswein, Oliver Just, Gabriel Martínez-Pinedo

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 with the goal of improve our understanding the evolution of stars, the nucleosynthesis of elements in the Universe and the observational signatures of the high-density equation of state and element synthesis.

Highlights in 2022

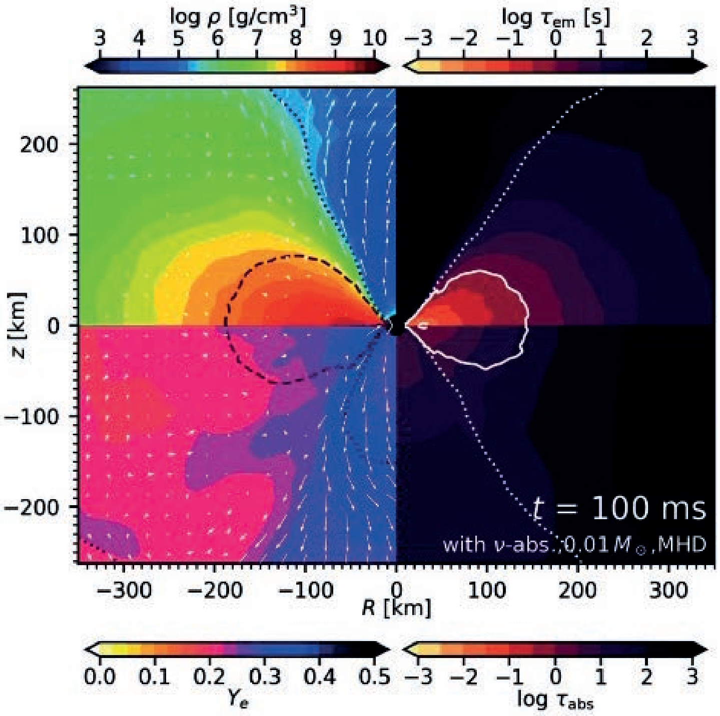

Figure 54. Black-hole torus simulations model the properties of outflows from these systems, which undergo the r-process to produce heavy elements. The figure shows the density, the electron fraction and time scales for neutrino reactions in a cut perpendicular to the equatorial plane. Figure adapted from [O. Just, S. Goriely, H.-T. Janka, S. Nagataki, and A. Bauswein, Monthly Notices of the Royal Astronomical Society 509, 1377 (2022)]

Several studies have been dealing with the nucleosynthesis via the rapid neutron capture process (r-process) in neutron star mergers and a special type of core-collapse supernovae, so-called collapsars which form a massive accretion torus around a central black hole. Similar black hole-torus systems can form in the aftermath of a NS merger and yield massive outflows producing heavy elements through the r-process. In [O. Just, S. Goriely, H.-T. Janka, S. Nagataki, and A. Bauswein, Monthly Notices of the Royal Astronomical Society 509, 1377 (2022)], we presented an extensive survey of the microphysical properties of such black hole tori and their outflows revealing a number on important dependencies on physical parameters but also on model ingredients. The publication has been accompanied by a press release and longer article in Germany’s largest popular astronomy journal “Sterne und Weltraum”.

Work on fast neutrino flavor conversions in the environment of torus outflows have been conducted [O. Just, S. Abbar, M.-R. Wu, I. Tamborra, H.-T. Janka, and F. Capozzi, Phys. Rev. D 105, 083024 (2022)]. In addition, the effect of many-body correlations in neutrino flavor evolution have been studied in simplified geometries with two and three neutrino beams for slow- and fast-type collective neutrino oscillations respectively. We demonstrated that quantitative deviation from the mean-field evolution can exist in a system of ~300,000 neutrinos for slow collective oscillations [Xiong, Phys. Rev. D 105, 103002 (2022)], and in up to thousands of neutrinos for fast collective oscillations [Roggero et al, Phys. Rev. D 106, 043022 (2022)], which calls for more careful examinations on the possible many-body corrections to neutrino oscillations in astrophysical environments

Two studies focused on the dynamical mass ejection of neutron star mergers and addressed the resulting r-process nucleosynthesis and electromagnetic emission (kilonova) based on sophisticated relativistic hydrodynamical merger models accounting for weak interactions [I. Kullmann, S. Goriely, O. Just, R. Ardevol-Pulpillo, A. Bauswein, and H.-T. Janka, Monthly Notices of the Royal Astronomical Society 510, 2804 (2022); O. Just, I. Kullmann, S. Goriely, A. Bauswein, H.-T. Janka, and C. E. Collins, Monthly Notices of the Royal Astronomical Society 510, 2820 (2022)]. We also contributed to a detailed analysis of the spectra of AT2017gfo, the kilonova associated with GW170817, and found further evidence for the presence of strontium in the outflow [J. H. Gillanders, S. Smartt, S. A. Sim, A. Bauswein, and S. Goriely, Monthly Notices of the Royal Astronomical Society 515, 631 (2022)]. A publication on a detailed hydrodynamical modeling of collapsars has found generally less favorable conditions for the synthesis of very heavy elements through the r-process [O. Just, M. A. Aloy, M. Obergaulinger, and S. Nagataki, Astrophys. J. Lett. 934, L30 (2022)]. Atomic opacities play a fundamental role for the modelling of kilonova light curves and spectra. A first study of atomic opacities has been published focusing on two key ions, Neodymium and Uranium, which are representative of Lanthanides and Actinides [Silva et al, Atoms 2022, 10, 18]. Kilonova models that explore the simultaneous production of Strontium and light elements have been published showing that is very unlikely to observe hydrogen and helium features in kilonova spectra [Perego et al, ApJ 925, 22 (2022)]

Other activities in the department concern the gravitational wave signal of neutron star mergers and efforts to constrain the high-density equation of state. We put forward an extensive study of the postmerger gravitational-wave emission of neutron star mergers [T. Soultanis, A. Bauswein, and N. Stergioulas, Phys. Rev. D 105, 043020 (2022)]. In this work, we identified new mechanisms shaping the gravitational-wave spectrum based on which we are now able to characterize basically all features of the gravitational-wave spectrum in the most relevant frequency range. In this paper we also devised analytic gravitational waveform models which are decisive for data analysis and parameter extraction from observations. These efforts exemplified the importance of secondary spectral features for the accurate modeling of gravitational-wave signals. We also continued to collaborate with gravitational-wave data analysis groups to develop specific pipelines for equation of state constraints showing that it will be possible to identify the occurrence of deconfined quark matter in the merger remnant by gravitational wave measurements [M. Wijngaarden, K. Chatziioannou, A., J. A. Clark, and N. J. Cornish, Phys. Rev. D 105, 104019 (2022)].

Electron capture processes play a fundamental role for the evolution of intermediate mass stars. We studied one of the last unknown transitions, the second forbidden transition from the ground state of ^{24}Na to the 2^+ state on ^{24}Ne, which determines the double electron capture rate on ^{24}Mg [D. Strömberg, G. Martínez-Pinedo, Phys. Rev. C 105, 025803 (2022)]. Pulsational pair-instability supernova are expected to be the end product of very massive star. Hydrodynamical simulations have been performed using energy-dependent three flavor neutrino transport that allow to identify the signatures of black hole formation both in the neutrino luminosities and gravitational wave signals [N. Rahman, H.T. Janka, G. Stockinger, S. E. Woosley, Monthly Notices of the Royal Astronomical Society 512, 4503 (2022)].

A promising candidate for Type Ia supernovae is the detonation of carbon-oxygen white dwarfs of less than 1.4 Solar masses, which provide good agreement with observations at early times (< 50 days). However, theoretical spectral modeling of the ejecta hundreds of days after explosion do not match observed spectra in the infrared region, mainly because the predicted ionization state is too high, which prevents the observed strong emission from Fe^+ [Shingles et al. MNRAS 512, 6150 (2022)] explore a possible reduction to the rates of ionization by non-thermal electrons and show that this brings spectral predictions much closer to observations.

Outlook for 2023

A fundamental goal of the research at the nuclear structure and astrophysics department is the development a complete pipeline of simulations codes that allow to obtain a complete picture of r-process nucleosynthesis in neutron star mergers. This involves radiation hydrodynamic simulations of the merger and the ejected material, nucleosynthesis network calculations including a microscopic description of the relevant rates, and radiative transport calculations of the kilonova light curves and spectra. We plan to advance in all this fronts in the near future. A new code for merger simulations is currently being developed that implements for the first-time moving mesh techniques in numerical relativity simulations. Furthermore, we plan to perform long-term radiation hydrodynamical simulations that follow 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 2022

- [1] Just, O. ; Goriely, S. ; Janka, H.-T. ; et al.: Neutrino absorption and other physics dependencies in neutrino-cooled black hole accretion disks. Monthly notices of the Royal Astronomical Society 509, 1377 (2022), DOI:10.1093/mnras/stab2861
- [2] Just, O. ; Aloy, M. A. ; Obergaulinger, M. ; et al.: r-process Viable Outflows are Suppressed in Global Alpha-viscosity Models of Collapsar Disks. The astrophysical journal / 2 934(2), L30 - (2022), DOI:10.3847/2041-8213/ac83a
- [3] Soultanis, T. ; Bauswein, A. ; Stergioulas, N.: Analytic models of the spectral properties of gravitational waves from neutron star merger remnants.Physical review / D 105(4), 043020 (2022), DOI:10.1103/PhysRevD.105.043020
- [4] Strömberg, D. F. ; Martínez-Pinedo, G. ; Nowacki, F.: Forbidden electron capture on 24Na and 27Al in degenerate oxygen-neon stellar cores. Physical review / C 105(2), 025803 (2022), DOI:10.1103/PhysRevC.105.025803
- [5] Shingles, L. J. ; Flörs, A. ; Sim, S. A. ; et al.: Modelling the ionization state of Type Ia supernovae in the nebular phase. Monthly notices of the Royal Astronomical Society 512(4), 6150 - 6163 (2022), DOI:10.1093/mnras/stac902

7.3 Hadron and QCD Physics

Head: Matthias F.M. Lutz, GSI
Author: M. F. M. Lutz and D. Mohler

The main objective of the Hadron and QCD Theory are predictions for the programme at FAIR with the focus on the future PANDA experiments. Particular emphasis is put on the synergetic application of two complementary methods in hadron physics: effective field theory (EFT) approaches for coupled-channel systems and simulations of QCD in discretized space-time (Lattice QCD).

Highlights in 2022

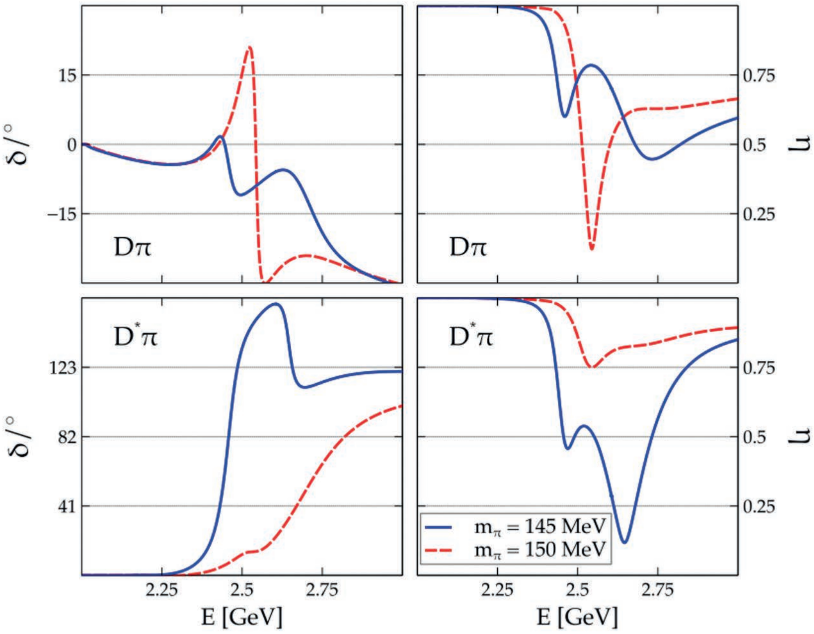

Figure 55. P-wave phase shifts with I=1/2 and $J^P = 1^-$ quantum numbers. The l.h. panels show the phase shifts, the r.h.p. the inelasticity parameters for the Dπ and D*π channels. Results are shown for two choices of the pion masses, m_π = 145 MeV and m_π = 150 MeV.

We performed an analysis of Lattice QCD data in the open-charm sector based on the chiral SU(3) Lagrangian. The low-energy constants were adjusted to recover the open-charm meson masses on Lattice QCD ensembles from HPQCD, ETMC and HSC with pion and kaon masses smaller than 550 MeV. A significant set of low-energy parameters was obtainable only if the most recent information from HSC on scattering observables is included in our global fit. For the first time our analysis considered the effect of left-hand cuts as developed in terms of a generalized potential approach (GPA). Here we used coupled-channel interaction terms at the one-loop level. The elastic s-wave and p-wave D π, D K and D bar-K scattering phase shifts on ensembles with nominal pion masses of about 239 MeV and 391 MeV were reproduced faithfully. Based on such low-energy parameters we predicted s- and p-wave phase shifts and inelasticities at physical quark masses, where the statistical uncertainties in the phase shifts are smaller than 1 degree always. Most striking would be the exotic s-wave D_s π channel, for which we predicted a resonance state at about 2.287 GeV where the phase shift passes through 90 degrees.

Based on such results, a first non-perturbative and unitary treatment of multichannel systems with anomalous thresholds based on realistic potentials was presented. We considered the isospin one-half example system, with D π, D η, D_s bar-K, D^* π , D^* η, D^* bar-K coupled channels in the $J^P = 1^-$ partial wave, chosen such that various phenomena that come with the opening of an anomalous threshold can be illustrated in a step-wise procedure by a suitable variation of up, down and strange quark masses.

For a pion mass of 150 MeV there are no anomalous thresholds encountered. The small change from 150 MeV to 145 MeV pion mass causes a dramatic impact of the anomalous threshold on the phase shifts showing that our results are highly relevant for the extrapolation of lattice QCD calculations towards the physical pion mass.

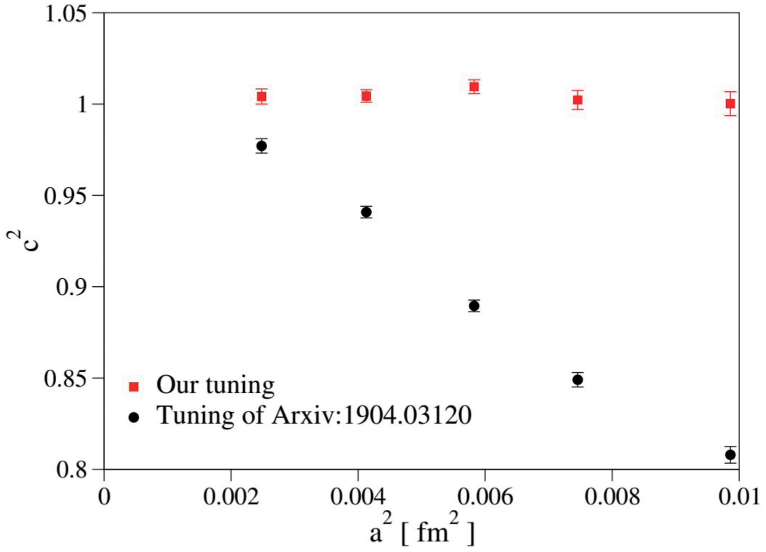

Figure 56. Speed of light squared for our action compared to the light-quark Wilson action used for the gauge configurations.

From the lattice QCD side we continued to focus on our infrastructure for future calculations of heavy-quark physics from lattice QCD. In this sector discretization effects are a concern for calculations employing finite-volume methods to extract scattering amplitudes. To remedy this situation we developed a novel tuning strategy for a relativistic heavy quark (RHQ) action previously used in the literature. Our strategy employs machine learning using a neural net to determine the optimal action parameters. With the usual light-quark action strong discretization effects are visible in the dispersion relation. Figure 56 shows that our action allows the tuning of the speed of light squared to the desired value removing such concerns.

In addition, 2022 saw a publication shedding further light on the puzzle encountered for the anomalous magnetic moment of the muon, where Standard Model calculations show strong tension with the measured values from the BNL and Fermilab experiments. In this publication we focused on the so-called “intermediate window observable”, where Lattice QCD calculations can be considered to be especially precise and reliable. In this window a pronounced tension with regard to the data driven method from the R-ratio entering the Standard Model calculation has previously been reported by the Budapest-Marseille-Wuppertal collaboration. Our results confirm this tension, which is shown in Figure 57.

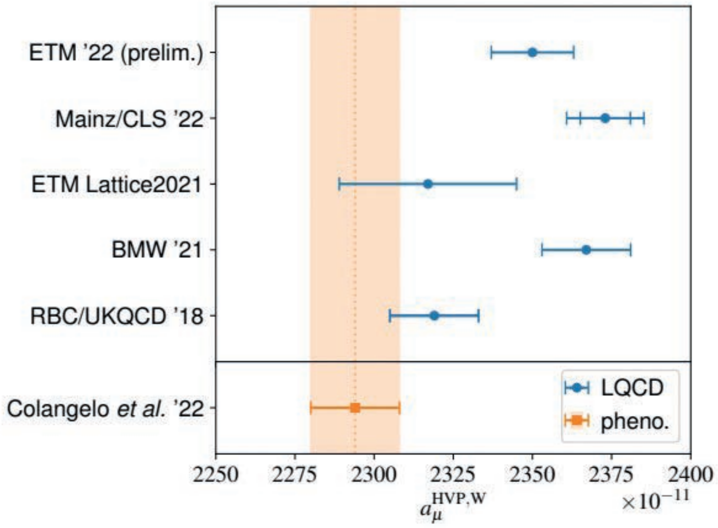

Figure 57. Lattice QCD results for the intermediate window quantity (blue) compared to the estimate of the data driven method (pheno). Our data is labeled as Mainz/CLS.

Outlook for 2023

For 2023 we plan to focus on scattering observables in open-charm and meson-baryon systems. For open charm systems we will further scrutinize the quark mass dependence of the amplitudes using the CLS gauge ensembles which will shed light on the possible existence of exotic hadronic states in this sector of QCD. Such studies in the open-charm systmes pave the way towards corresponding challenges in meson-baryon systems with strangeness as will be copiously be produced soon in day one experiments at PANDA.

First coupled-channel Lattice QCD results for strange baryons will be obtained. This is complemeted by an EFT project. We plan to analyze state of the art Lattice QCD data on baryon masses, and from there determine a large set of low-energy constants required for the description of coupled-channel effects in meson-baryon scattering. Particular emphasis is put on reaction amplitudes, that cannot be measured in the laboratory directly, but are neverthelss important input for transport model simulations of heavy-ion reactions.

Selected publications of 2022

- [1] Lutz, M. ; Guo, X.-Y. ; Heo, Y. ; et al.: Coupled-channel dynamics with chiral long-range forces in the open-charm sector of QCD. Physical review / D 106(11), 114038 (2022), DOI:10.1103/PhysRevD.106.114038
- [2] Korpa, C. L. ; Lutz, M. F. M. ; Guo, X.-Y. ; et al.: Coupled-channel system with anomalous thresholds and unitarity.Physical review / D 107(3), L031505 (2023), DOI:10.1103/PhysRevD.107.L031505
- [3] Hudspith, R. J. ; Mohler, D.: Fully nonperturbative charm-quark tuning using machine learning. Physical review / D 106(3), 034508 (2022), DOI:10.1103/PhysRevD.106.034508
- [4] Cè, M. ; Gérardin, A. ; von Hippel, G. ; et al.: Window observable for the hadronic vacuum polarization contribution to the muon g − 2 from lattice QCD. Physical review / D 106(11), 114502 (2022), DOI:10.1103/PhysRevD.106.114502

8. Collaborations & cooperations

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

Head: Prof. Dr. Henner Büsching (JWGU Frankfurt, GSI)
Authors: Henner Büsching, Gerhard Burau

The GSI Helmholtzzentrum für Schwerionenforschung GmbH and its accelerator facility FAIR provide an excellent environment for doctoral research and structured doctoral training. In strong cooperation with its partner universities young researchers are prepared optimally for future careers inside and outside of 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 high level educational measures, the graduate school provides individual support as primary contact and care center for doctoral students in its program. By the end of 2022, more than 340 doctoral researchers, who perform their research on GSI-FAIR related topics, are registered as participants in the HGS-HIRe program. 79 of them have been newly accepted for participation in the program of HGS-HIRe during 2022, 34 doctoral researchers affiliated with HGS-HIRe finished successfully their doctoral projects in 2022. The transformation of the governance structure of the graduate school to better adjust to the organizational structure of GSI-FAIR, the appointment of the HGS-HIRe Management Board as well as the HGS-HIRe Application Review Committee has been completed and has been fully implemented in 2022.

Though the impact of the COVID-19 pandemic on the HGS-HIRe program was still challenging in 2022, the gradual ease of the situation over the year allowed for an increase in the graduate school's program activities; in particular, it led to a significant increase in the demand for individual travel funds by the HGS-HIRe participants as a consequence of enhanced conference and workshop participation. Furthermore, it allowed for a restart of face-to-face program elements to second the HGS-HIRe online events established during the pandemic. The following face-to-face training and information events are particularly worth mentioning here:

- HGS-HIRe Participant Education Project on Machine Learning – a workshop that was dedicated to the mentioned topic with more introductory lectures, real-world use cases and hands-on sessions.
- HGS-HIRe Perspectives – an event series that addresses the question „What's next after finishing the doctoral research?" and brings together professionals from applied science or industry who graduated in natural science and current HGS-HIRe participants.
- Last but not least, the International Summer Student Program at GSI-FAIR which was held again in 2022 after a pandemic-related break of two years.

In its transferable skills training program, in 2022 HGS-HIRe was able to offer a similar high number of training events as in the previous year. Altogether, in 2022 thirteen highly interactive transferable skills courses as part of an integrated series of courses, covering beginner and advanced courses, with a total of more than 250 participants have been organized and conducted by HGS-HIRe together with the experienced trainer team from Great Britain. The courses were organized as online courses or again as face-to-face courses. As in previous years it was possible to attract doctoral researchers from other Helmholtz Graduate and Research Schools, leading to a more interdisciplinary learning environment and group structure in the transferable skills courses and, moreover, an ongoing strengthening of the Helmholtz-wide network and spirit.

Furthermore, 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 proved very valuable, again. In this context, the following supporting information and training events particularly complemented the program offers in 2022:

- Quarterly HGS-HIRe Information & Contact Sessions for participants
- HEPTrepreneurs episodes by HEPTech in collaboration with the Technology Transfer (TT) Divisions at GSI and CERN
- Helmholtz workshops Young Entrepreneurs in Science and Start-up Days 2022, and various event offers of the Helmholtz Open Science Office.

Moreover, HGS-HIRe expanded its information platform for participants on additional advisory offers and services at GSI-FAIR and the partner universities as well as internal and external online courses and training events within, e.g., the Helmholtz network. Among these, external online and residential 'power weeks', i.e. training events on more specialized scientific and technical aspects and methods, as the Helmholtz Incubator Summer Academy, the Helmholtz GPU Hackatron 2022, 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 2022.

In summary, in 2022 HGS-HIRe welcomed opportunities of the gradual ease of the pandemic situation to strengthen its structured program offers including online and face-to-face training courses and supportive information events. Opportunities to enhance the program by stronger cooperation within the Helmholtz community have been taken. It became apparent that this development not only has a positive impact on the HGS-HIRe program under a pandemic situation but also on activities of HGS-HIRe in a post-pandemic setting. Combinations of online offers and re-established face-to-face events, as, e.g., HGS-HIRe lecture or power weeks have been realized in 2022 and are planned for the future. This will increase the variety of attractive program elements for the participants of HGS-HIRe even further, and will complement the excellent GSI-FAIR research and training environment for young researchers.

8.2 Helmholtz Research Academy Hesse for FAIR

Head: Prof. Dr. Dr. h.c. Marcus Bleicher (Goethe University Frankfurt, GSI)
Author: Frank Nerling (GSI, Goethe Univ. Frankfurt)

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 programme 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 programme 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 programme 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 programme advisory board.

Highlights in 2022

A highlight in 2022 was the organization of the 15th edition of the prestigious international Conference QWG2022 as a HFHF event hosted at GSI Darmstadt [QWG2022, 15th International Workshop on Heavy Quarkonium, Sep 22 – 23, 2022, GSI Darmstadt, Germany]. More than 150 leading scientists from research centers and universities all over the world convened at GSI/FAIR in a meeting of the international Quarkonium Working Group (QWG). For a week, the world leading experts intensively discussed the latest experimental results, theoretical developments, and new prospects for heavy-quarkonium physics. The QWG chose to convene at GSI/FAIR in strong appreciation, support and expectation for the upcoming FAIR facility. The future PANDA experiment (antiProton ANnihilation at Darmstadt) at FAIR will offer a broad physics programme, covering different aspects of the strong interaction and will play a key role for quarkonium physics.

HFHF events in 2022 (organized or supported by HFHF)

- FAIRness 2022 “FAIR next generation scientists – 7th Edition Workshop” Organizers: A. Bauswein (chair), M. Destefanis, T. Galatyuk, A. Gumberidze, C. Ratti and L. Tolos, May 23 - 27, 2022, Pieria, Greece
- Karpacz Winter School 2022 “Young scientists’workshop and 58th Karpacz Winter School of Theoretical Physics – Heavy Ion Collision: From First to Last Scattering” Organizers: P. Huovinen & D. Blaschke (chair), T. Fischer, M. Marczenko, V. Mykhaylova, K. Redlich, M. Szymanski, June 19 - 25, 2022, Karpacz, Poland
- HIAT 2022 “The 15th International Workshop on Heavy Ion Accelerator Technology” Organizers: F. Herfurth

(chair), W. Barth, W. Geithner, R. Hollinger, F. Maimone, H. Podlech, S. Reimann, , M. Stein, U. Weinrich, June 27 – July 1, 2022, Darmstadt, Germany

- Erice Summer School 2022 “43rd International School of Nuclear Physics” Organizers: M. Buballa and C. Fischer, Sep 16 -22, 2022, Erice, Sicily
- QWG 2022 “The 15th International Workshop on Heavy Quarkonium” Organizers: F. Nerling (chair), K. Götzen, U. Kurilla, A. Meergans, D. Mohler, M. Wagner, Sep 26 -30, 2022, GSI Darmstadt, Germany

Selected publications of 2022

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8.3 ExtreMe Matter Institute EMMI

Head: Prof. Dr. Peter Braun-Munzinger (Univ. Heidelberg, GSI)
Author: Carlo Ewerz (Univ. Heidelberg, GSI)

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 focussed 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)

EMMI events in 2022

Half an EMMI Day on 2-2-22", Organizers: P. Braun-Munzinger, C. Ewerz, A. Schwenk, February 2, 2022, online
EMMI Workshop "100 Years of Nuclear Isomers", Organizers: P. Walker, A. Pálffy, Y. Litvinov, May 2-4, 2022, Harnack House, Berlin, Germany
EMMI RRTF "Nuclear physics confronts relativistic collisions of isobars", Organizers: G. Giacalone, J. Jia, V. Sornà, Y. Zhou, Part 1: May 30 - June 3, 2022, U Heidelberg, Germany
ECT*-EMMI/GSI Workshop "Connections between cold atoms and nuclear matter: From low to high energies", Organizers: C. Sa de Melo, A. Gezerlis, June 6-10, 2022, Trento, Italy / online
ECT*-EMMI/GSI Workshop "Neutron Stars as Multi-Messenger Laboratories for Dense Matter", Organizers: I. Tews, B. Giacomazzo, S. Guillot, J. Margueron, S. Nissanke, June 20-24, 2022, Trento, Italy / online
EMMI Workshop "HITRAP Facility and Experiments - Status and Future Perspectives", Organizers: Z. Andelkovic, F. Herfurth, W. Quint, R. Schuch, T. Stöhlker, M. Vogel, July 17-20, 2022, Eisenach, Germany
EMMI RRTF "Real and virtual photon production at ultra-low pT and low mass at LHC", Organizers: S. Flörchinger, R. Bailhache, K. Schweda, Part 2: August 1-5, 2022, GSI, Darmstadt, Germany
EMMI Workshop "Long-Range Interactions in Quantum Systems", Organizers: A. Browaeys, F. Ferlaino, R. Löw, September 6-9, 2022, Innsbruck, Austria
EMMI Workshop "Meson and Hyperon Interactions with Nuclei", Organizers: S.D. Bass, K. Itahashi, V. Metag, T. Saito, C. Scheidenberger, Y. Tanaka, September 14-16, 2022, Kitzbühel, Austria

EMMI Workshop "New Vistas in Photon Physics in Heavy-ion Collisions", Organizers: I. Grabowska-Bołd, M. Kłusek-Gawenda, R. Schicker, A. Szczurek, September 19-22, 2022, Polish Academy of Sciences and AGH University, Krakow, Poland

EMMI RRTF "Nuclear physics confronts relativistic collisions of isobars", Organizers: G. Giacalone, J. Jia, V. Sornà, Y. Zhou, Part 2: October 12-14, 2022, U Heidelberg, Germany

EMMI & IReNA Workshop "Remnants of neutron-star mergers - connecting hydrodynamics models to nuclear, neutrino, and kilonova physics", Organizers: O. Just, J. Barnes, S. Giuliani, M.-R. Wu, October 17-20, 2022, GSI, Darmstadt, Germany

EMMI Workshop "Accurate relativistic treatment of multi-electron atoms and applications to Super-Heavy elements", Organizers: P. Indelicato, P. Schwerdtfeger, October 24-26, 2022, Paris, France

EMMI Workshop "2nd International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022)", Organizers: T. Nakamura, K. Shigaki, H. Ohnishi, H. Tamura, Y. Takahashi, M. Horikoshi, E. Hiyama, Y. Kondo, October 31 - November 3, 2022, Sendai International Center, Sendai, Miyagi, Japan / online

EMMI RRTF "Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC", Organizers: A. Andronic, P.-B. Gossiaux, P. Petreczky, R. Rapp, M. Strickland, Part 2: December 12-16, 2022, GSI, Darmstadt, Germany

9. Accelerator operations and operation of the infrastructure support

Interims head: Udo Weinrich

The GSI Helmholtzzentrum für Schwerionenforschung operates on its campus in Darmstadt a large, world-wide unique heavy-ion accelerator complex consisting of the UNILAC linear accelerator that accelerates particles from H to U up to 11 MeV/u, the SIS18 synchrotron for further acceleration up to energies of 2 GeV/u, and the experimental storage cooler ring ESR capable of storing and cooling and even decelerating exotic and highly-charged ions at energies from 4 MeV/u to 0.5 GeV/u.

Also a further storage cooler ring – CRYRING, with a large Swedish FAIR in-kind contribution, is now in operation downstream the ESR, for atomic and nuclear physics experiments at lower energies of about 15 MeV/u down to a few 100 keV/u. In addition to proton and ion beams, pion beams can be provided at GSI in a momentum range from 0.5 to 2.5 GeV/c.

9.1 Executive summary

Author: Udo Weinrich

In 2022 the business area accelerator operations (ACC) successfully carried out the physics run in the first half of the year. In addition, ACC continued its effort to contribute to the various FAIR project tasks well as leading the upgrade program of the existing GSI accelerator facility.

The COVID-19 pandemic situation still imposed quite some constraints to the daily work. Nevertheless, the user beam time could be executed successfully. A very high level of parallel operation with many ion sources towards many different target stations was performed. This enabled a maximum of scientific output in the restricted operation time. The drawback of this mode of operation was the very high stress level for operations team in charge.

One highlight of the beam time was the restart of the commissioning of HITRAP with ions from the ESR. Deceleration to RFQ output energy could be demonstrated. The foreseen final beam test of the cw-linac advanced demonstrator could not be performed due to delayed component deliveries. The test is now scheduled for end of 2023.

In September the beam time Retreat 2022 took place. This workshop was organized as an in presence meeting for three days at the Lufthansa Center Seeheim. This enabled after two years of COVID-19 restrictions a very fruitful exchange of accelerator and experiment experts. The focus was on preparation of the upcoming beam times – with lessons learned from the 2022 beam time. In addition the consequences of increased electricity and procurement costs for beam time scheduling were addressed.

In July 2022 started a major shutdown of one year duration with a lot of refurbishment work in the area of technical infrastructure like medium voltage switch gears and air cooling system for technical areas. In parallel significant repair work is taking place in the accelerator area. Although most of the work could be started in time several challenges arose. Delivery delays - especially of electrical components – made the flexible readjustment of working order necessary. In the ESR electron cooler a significant amount of asbestos and synthetic mineral fibres was found and triggered the development of a concept for safe working conditions to deal with this. This, however, also generated a delay of the execution of the repair work towards 2023.

Again a lot of progress was made in the upgrade project for the UNILAC post-stripper. Several orders for the production of the series components were placed. The production of the tank mantles and end caps is already in full swing. Deliveries on the GSI campus are planned to start in spring 2023. The challenge in this project is now in providing sufficient areas for preparation of the components for the copper coating and the treatment afterwards.

ACC also continued its commitments to the FAIR project in leading the work packages of the p-Linac proton source, p-Linac RF as well as for the stochastic cooling for the Collector Ring (CR). Taking into account the evolution of the FAIR Project – especially the relation to the deliveries of Russia and the overall financial situation – a review of the corresponding activities with respect to further execution was started.

The ACC units galvanic workshop, the mechanical workshop and technology laboratory continued to support design, construction and integration of FAIR components. Of large interest in this respect is the final phase of the refurbishment of the “Tankverkupferungshalle” – the building for the Galvanic workshop. It is planned to restart the copper coating facility in spring 2023.

The FAIR subproject “FAIR-commissioning” under the leadership of the business area ACC is continuing to take shape. In lean commissioning workshops important workflows were discussed. The attribution of project responsibles took place, the scheduling process started and a first risk assessment was conducted and presented.

In November 2023 the upgrade strategy for the existing GSI accelerator system towards nominal FAIR performance was presented to the MAC (Machine Advisory Committee). The committee endorsed the chosen approach. Due to very limited financial ressources the upgrade program is focused in the UNILAC area on the hydrogen operation of the pulsed gas stripper and the refurbishment of the control system.

The details on the above mentioned activities and their outcome will be reported in the following chapters.

9.2 Beam time 2022 - operation and availability

Authors: Markus Vossberg, Oksana Geithner, Miriam Klich, Stephan Reimann

Operation

Figure 58. The diagram (left) shows the different event durations during the experimental beamtime 2022. 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. Between the end of March and end of June, there was an average of about four experiments in parallel operation. An exception is the week from June 6th, in which mainly machine experiments took place, which are not taken into account in this diagram. The parallel factor over the entire experimental beamtime is 2.6 and was lower than in previous year, which can be attributed to the exclusive proton beamtime. The right picture shows the overall availability for the experimental beamtime 2022.

The physics run 2022 within the FAIR Phase-0 started on February 2nd, after a conditioning phase for the UNILAC-RF of 3 weeks parallel to the hardware commissioning and a short beam-recommissioning phase. The beamtime ended on June 30th, and included 3 shorter machine beamtime blocks used mainly for machine studies and to test special beam settings. During this beamtime, a total of 13 different types of ions with different energies and charge states were accelerated and made available to the experiments. The beamtime started with a 45-day long proton block. The proton beam was provided by two different ion sources, the high-current source with CH_3^+ and the ECR source with H_2^+. The main user of the protons from the high-current source was the HADES experiment, which needed a stable beam with maximum rigidity over the entire period. After the proton beamtime the UNILAC accelerators had to be re-conditioned so that the cavities could run at higher power levels for the subsequent heavy ion operation. This was followed by a uranium block lasting about 20 days, where different experiments were supplied with beam in the caves HTA, HTD, HHT and the ESR. In parallel, calcium beam was provided for the UNILAC experiments in X8, Y7 and M1-3, and an iron beam for the caves HTA and HTM. The mixed operation from the three different ion sources started in May. Up to seven experiments with frequently changing types of ions with various energies were served with beam in parallel. The various experiments with different requirements resulted in a very busy beamtime schedule with an average parallel operation factor of about 2.6 (Figure 58). This meant always new settings and adjustments to the machine, especially in the period from end of March to end of June. The very ambitious and packed beamtime schedule led to the fact that the majority of the operators had to be continuously scheduled on rotating shifts for 5 months without a break. 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 for the entire period. The corona pandemic also led to some restrictions and an increased probability of staff shortages during this beamtime. However, a successful beamtime could finally be delivered due to the very high motivation and flexibility of the specialist groups and operators.

Availability

The work of the availability working group was continued this year to further improve the statistical basis of failure statistics by assigning errors that occurred to the appropriate specialist groups and verifying their root cause. At the end of the beamtime, each expert group discussed a summary of the errors in order to work out possible improvements. The total time of all ongoing experiments in parallel operation mode was about 8500 hours. An overall availability of 86% was reached for the experimental beamtime. During this 72% of the beam was successfully delivered to the users with an average downtime of 14% (1150 h). During this operation period, there were many short circuits within the UNILAC RF-cavities, which led to interruption of the entire beam operation. The aging of the structures is assumed to be the main cause of the approximately 500 failures. A defect microwave generator of the CRYRING ECR source with a downtime of 160 h caused the longest interruptions. The main reason for the long outage was that there were no CRYRING on-call services at night or during the weekend, (a switch to MINIS ion-source was decided). Another interruption was caused by the septum GE01MU4MI due to a negative measured current at the direct-current current transformer (DCCT) (100 h), and a quench caused a failure at the electron cooler in CRYRING (70 h). Due to a cooling water problem, an internal triplet of the HLI-IH overheated. The associated power supply unit did not switch off. Parts of a quadrupole magnet have melted. The corresponding magnet in the triplet was shut down and caused a failure of 30 hours. In recent years, it has increasingly become the case that the infrastructure for cooling water and air is sometimes working at its upper limit. For example, the flow rate of the KS02 cooling circuit, due to the not efficient pumping, is too low. Especially during the summer months, the air temperatures in the TH- and EX-halls are increased. The hardware in these areas can no longer be adequately cooled if the temperatures are too high. The manual opening of the roof windows and the installation of additional fans in the racks provided a temporary solution, but this workaround must be replaced by a permanent solution in the future.

9.3 Ion source operation at GSI

Authors: Ralph Hollinger, Alexandr Andreev, Aleksey Adonin, Rustam Berezov, Frank Heymach, Ralf Lang, Jan Mäder, Fabio Maimone

In 2022 the ion source department provided various types of ion beams for user beam time as well as for machine experiments. 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 of the High Current Injector (HSI) and the ECR Ion Source (ECRIS) at High Charge State Injector (HLI) were supplying the UNILAC in parallel operation. The following table shows the ion species delivered to the accelerator. Representative intensities of the analyzed beam in front of the HSI-RFQ and of the HLI-RFQ are depicted.

The PIG source provided stable operation of the following ion species: $^{56}Fe^{2+}$, $^{40}Ar^{2+}$, $^{209}Bi^{4+}$, $^{197}Au^{6+}$, $^{136}Xe^{6+}$ at a life time of up to 70 hours. Several highlights could be achieved during the beam time 2022, such as the first production of $^{58}Ni^{1+}$ for the HITRAP commissioning and the production of $^{6}Li^{1+}$ from enriched material, manufactured by HMW Hauner GmbH and prepared for operation by the IOS workshop for NUSTAR SFRS and biophysics user programs. During the production of $^{197}Au^{8+}$ dedicated to the material research program, a Ta-shield of the ion source chamber was destroyed. This leads to a slow reduction of the ion current due to bad vacuum in the chamber caused by charge exchange effects. However, this problem was solved short term by speedy exchange of the Ta-shield, although it took a weekend in order to detect the failure. Another failure occurred at the more than 40 years old 5000 liter turbo pump at the DC post acceleration gap. The broken pump has been substituted by another prepared pumping system during the short eastern shut down.

Ion species	Duty Cycle*	Analyzed Beam Intensity / emA	Ion Source	Duration (days)
$^{1}H_2^+$	dc	0.21	ECR	45
$^{6}Li^{1+}$	5 Hz / 1 ms	0.1	PIG	10
$^{15}CH_3^+$	1 Hz / 0.5 ms	2**	MUCIS-1990	57
$^{36}O_2^+$	1 Hz / 0.5 ms	4	VARIS	7
$^{40}Ar^+$	1 Hz / 0.5 ms	8**	CHORDIS	13
$^{40}Ar^{2+}$	5 Hz / 1 ms	0.3	PIG	6 (OP-Training)
$^{40}Ar^{8+}$	dc	0.2	ECR	18
$^{48}Ca^{10+}$	dc	0.08	ECR	45
$^{56}Fe^{2+}$	5-10 Hz / 1 ms	0.1	PIG	8
$^{58}Ni^{1+}$	5 Hz / 1 ms	0.27	PIG	12
$^{136}Xe^{6+}$	25 Hz / 5 ms	0.17	PIG	6
$^{197}Au^{4+}$	1 Hz / 0.35 ms	4	VARIS	7
$^{197}Au^{6+}$	5 Hz / 1 ms	0.3	PIG	12
$^{197}Au^{8+}$	25 Hz / 1 ms	0.04	PIG	11
$^{208}Pb^{4+}$	1 Hz / 0.4 ms	6	VARIS	17
$^{209}Bi^{4+}$	5 Hz / 1 ms	0.15	PIG	7 (1st Block)
$^{209}Bi^{4+}$	5 Hz / 1 ms	0.15	PIG	3 (2nd Block)
$^{238}U^{4+}$	1 Hz / 0.45 ms	10**	VARIS	26 (Physics run)
$^{238}U^{4+}$	1 Hz / 0.45 ms	10**	VARIS	12 (Machine experiments)

* Duty cycle from ECR is always 100%, UNILAC provides a maximum of 50 Hz / 5 ms
** Beam intensity was reduced by collimation slits in front of the HSI-RFQ

Operation of high current ion sources (MUCIS-1990, CHORDIS and VARIS) from Terminal North also brought a few notable highlights in 2022. One of them is a longest run of MUCIS-1990 with methan gas, providing the accelerator with CH_3^+ molecular ion beam. 57 days of stable operation with only one short service for filament exchange. With the beam intensity of 2 emA in front of the HSI-RFQ (limited by using slits in the beamline) it was possible to achieve 0.9 emA of H^+ beam and 1 emA of C^{6+} beam at the end of the transfer channel, that corresponds to $5.5 \cdot 10^{11}$ particles and $1 \cdot 10^{11}$ particles in 100 µs pulse for H^+ and for C^{6+}, respectively.

Another highlight achieved at beamtime 2022 is the high availability of the ion beams from the high current ion sources (represented in the Table below):

Ion species	$^{15}CH_3^+$	$^{36}O_2^+$	$^{40}Ar^+$	$^{197}Au^{4+}$	$^{238}U^{4+}$
Beamtime duration	57 days	7 days	13 days	7 days	38 days
Total operation* time	500 h	117 h	291 h	164 h	646 h
Total service** time	6 h	3 h	2 h	3 h	8 h
Total beam interruption time	0 h	3 h	2 h	3 h	8 h
Ion beam availability	100%	97%	99%	98%	99%

* total up time when the ion source was in operation mode

** including ion source installation and commissioning when changing elements (ion species)

In spite of quite successful overall operation of high current sources, Pb-208 beam delivery became complicated. In order to provide high current $^{208}Pb^{4+}$ ion beam, the cathodes out of a composite material: Pb-Cu (40% Wt.) with a special structure (Cu litz-wire structure filled with enriched Pb-208, manufactured by Fa. Hauner) are applied inside VARIS. Previously, such cathodes showed sufficient operation stability providing 6 emA of Pb^{4+} ions with a lifetime of a single cathode of more than 24 hours. In the second lead beam block the cathodes from the last production charge (Dec. 2020) have been used. Unexpectedly, all cathodes of this production charge showed a similar behavior: a sufficient performance with ion source beam current of 5 emA at the beginning (first 30 minutes of operation) followed by an operation phase with a notable reduction of the beam intensity to 2-3 emA as well as the appearance of strong pulse-to-pulse instabilities. Due to such an untypical behavior the lifetime of the cathodes was reduced to 3-5 hours and, as a result, the ion source must be serviced every 2-3 days. Moreover, this caused complicate tuning procedures of the ion beam at UNILAC. Further investigations of this cathode issue are still ongoing.

The ECRIS at the HLI has been in operation to provide $^{1}H_2^{+}$, $^{48}Ca^{10+}$, and $^{40}Ar^{8+}$.

The proton beam was delivered to the user experiments without any further interruption or post-optimization of the ECRIS settings for more than six weeks continuously of operation. An excellent beam quality has been achieved since a beam current of up to 220 eμA was delivered with high stability for the entire beam block.

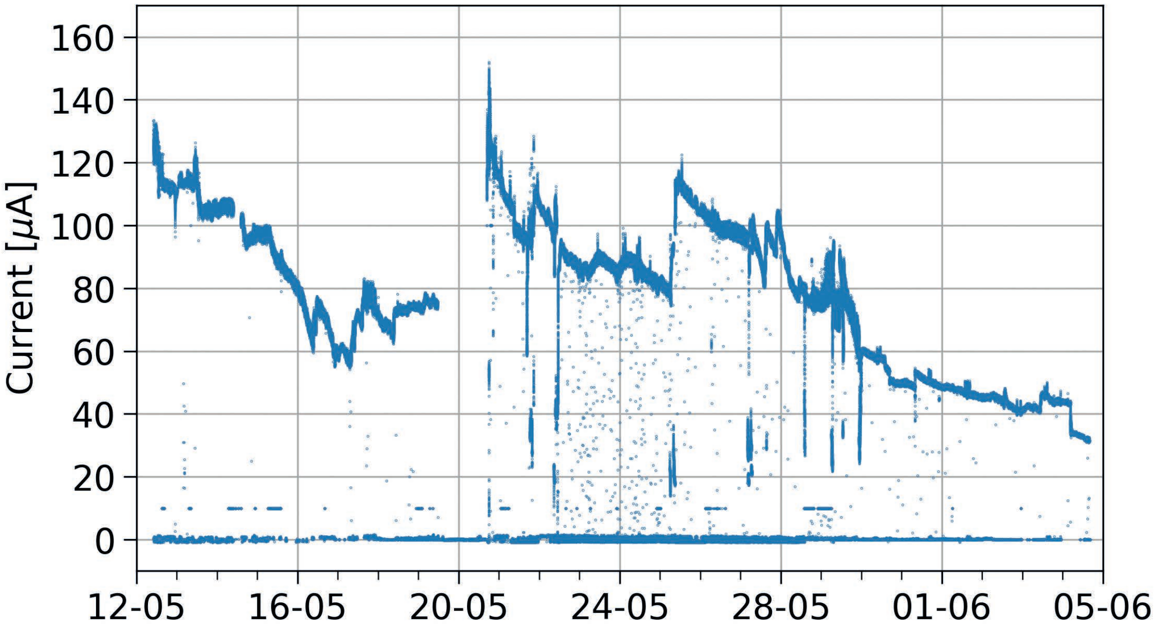

Figure 59. $^{48}Ca^{10+}$ beam current measured in front of the RFQ at HLI during the second Ca block.The x-axis represents the date from 12th of May to 5th of June.

The $^{48}Ca^{10+}$ ion beam has been requested by the experiments of the Super Heavy Element (SHE) groups and by the material research, plasma physics, and nuclear physics user program. The highest beam intensity (150 eμA) has been achieved. However, this current level has not been delivered for the entire calcium beam time. These drawbacks, already detected whenever an higher intensity is requested, are shown in Figure 59, where the $^{48}Ca^{10+}$ intensity measured at the beam current transformer in front of the RFQ is plotted for the second calcium beam block. In order to achieve higher intensities, the oven power must be increased. As a result, from the beginning of the operating phase too much material was deposited inside the plasma chamber and the internal components. Furthermore, the beam stability turned moderate and several interventions to optimize the ECRIS settings were requested for this issue.

Stable $^{40}Ar^{8+}$ ion beam has been delivered with an high beam intensity of up to 210 eμA to the SHIP experiment.

9.4 UNILAC operation report

Authors: Hartmut Vormann, Uwe Scheeler, Winfried Barth, Markus Vossberg

In 2022 the UNILAC was in operation for 107 days of user beamtime, five days have been used for operator training, 26 days for RF-tuning and 10 days for machine experiments. Before the start of the user beamtime, extensive RF and beam commissioning took place.

The beamtime started with a six week block of proton and carbon ($^{12}C^{6+}$) beam, generated from methane molecules CH_3 by the MUCIS (Multi Cusp Ion Source), and lithium beam ($^{6}Li^{1+/3+}$) from the Penning Ion Source (PIG).

The next block was dominated by high intensity Uranium beam (^{238}U) from the Vacuum ARc Ion Source (VARIS) for the synchrotron SIS18, and high duty factor calcium beam ($^{48}Ca^{10+}$) from the High Charge State Injector (HLI) delivered by the Electron Cyclotron Resonance Ion Source (ECRIS) for UNILAC users. Additionally, iron (^{56}Fe) beam from the PIG has been provided for the SIS18. At the end of the user beam period the Uranium beam was also used for a machine investigation campaign applying the pulsed hydrogen gas stripper [1, 2]. Before this, one week of strong high power RF conditioning has been accomplished. Due to the strong interaction with the RF-conditioning simultaneous iron beam operation for detector calibration purposes was cancelled.

In the following the $^{48}Ca^{10+}$ (ECRIS) beam for the UNILAC users was continued, accompanied by lead (^{208}Pb) from the VARIS, bismuth (^{209}Bi) from the PIG, oxygen (^{18}O) from the VARIS, nickel (^{58}Ni) from the PIG, carbon (^{12}C) from the MUCIS by cracking CH_3, and argon (^{40}Ar) beam from the Cold or HOt Reflex Discharge Ion Source (CORDIS), all delivered to the SIS18.

Further on gold beam for the SIS18 from the PIG and later with high intensity from the VARIS have been provided by the UNILAC; in parallel, five days of machine experiments with high current argon beam (CORDIS) and ten days with high duty factor argon beam (ECRIS) for the SHIP experiment were performed. Finally, lead (^{208}Pb) from the VARIS and xenon beam (^{136}Xe) from the PIG could be successfully accelerated.

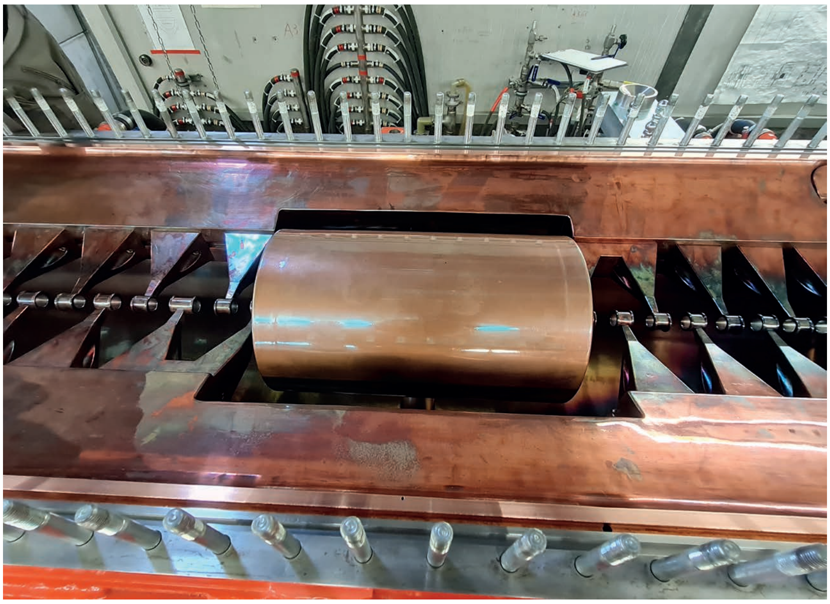

Figure 60. First triplet of the HLI-IH, with one quadrupole inside damaged (not visible).

Beam operation was suffering from various failures and interruptions: As the repair of an Alvarez drift tube could not be finished before start of the beamtime 2022, a pair of focusing quadrupoles inside the Alvarez tank A I was still out of operation.

The dipole septum magnet supplying the Z-branch was out of operation since a leakage occurred end of November 2021. This did not affect the beamtime, since no experiments were scheduled in the Z-branch. A new septum magnet coil is already ordered and will be delivered by the end of 2022.

As the leak of the large gold seal in the Alvarez A II between tank sections 2 and 3 was repaired immediately in the short winter break, A II was in operation without any restrictions.

During commissioning in January 2022 the RF-coupler of the HLI RFQ became leaking and was replaced and recommissioned in two days.

The re-buncher between the Alvarez cavities A III and A IV was temporarily out of operation, as its plunger actuator potentiometer did not work properly. In addition to that, its RF coupler became leaking and was replaced within four days, during which a new loop was fabricated and brazed into a spare part.

In May 2022 the first focusing triplet of the HLI-IH was partially damaged (Figure 60). In order to avoid further damage caused by water leakage, the cooling water supply was manually stopped. While almost all interlock switch-offs worked well, the power converter supplying one quadrupole of this triplet did accidentally not switch off. This quadrupole was overheated and as a consequence taken out of operation. The beamline setting was successfully adapted in order to compensate the missing quadrupole. Besides, the polarities of the remaining two quadrupoles in the triplet have been reversed. Tendering for a new triplet has now started. HLI operation was additionally affected due to a blocked cooling water filter at the ECRIS.

Alvarez RF-amplifier failures occurred frequently - remarkable is the defect of the A IV final stage tube anode capacitor at the end of June, when the beamtime could be continued successfully after a concentrated repair action of the UNILAC RF department staff.

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9.5 SIS100/SIS18

Author: Jens Stadlmann

SIS18 operation report

The SIS18 was operated in three blocks for experiments and machine studies with short breaks in between from January to March, March to April and April to June respectively.The first block started with proton beam for different users with fast and slow extraction. Proton beam operation above transition energy could be provided as regular operation in 2022 after it had been established in test runs 2020/21. Especially the rather high demands for beam stability and micro spill structure quality by the HADES experiment could be fulfilled with slowly extracted protons of 4.5 GeV energy. Other ion species provide for experiments in the first block were Lithium, Carbon, Iron.The second block was dominated by Uran operation. At the start of the third block we did machine studies aiming for highest uranium intensities for future FAIR operation. The booster mode for injection into the future FAIR synchrotron SIS100 was successfully demonstrated for the first time. The third block started with Bismuth and Lead beam. Other ion species used at the SIS18 were, Oxygen, Nickel, Carbon, Argon and Gold.

Damage to extraction septum

In the transition from the second to the third block the electrostatic extraction septum used for slow extraction was damaged. The damage most likely occurred during the Uranium operation for machine studies. The septum could not provide the full deflection angle at highest rigidities after the incident. This could be compensated at lower beam extraction energies. At higher extraction energies higher losses at the magnetic extraction septum were accepted to continue operation. The septum is scheduled to be repaired in the shutdown 2022/2023. It is expected that about one third of the septum wires have been destroyed.

Conclusion

The beam-time 2022 was conducted with full parallel operation of several experiments and ion species during the same operation phase. Despite the very demanding beam-time schedule most of the experiments using SIS18 beam could be conducted with satisfactory beam quality. The overall machine availability of the SIS18 was good. Despite the major damage to the extraction system in between block two and three we could compensate and continue to deliver beam to experiments in the third block.

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9.6 ESR operation and status

Authors: Markus Steck, Regina Heß, Ronald Joseph, Sergey Litvinov, Bernd Lorentz, Ulrich Popp

As in the previous year the ESR storage ring was operated for FAIR Phase-0 experiments over a period of about three months. The available time with beam was largely devoted to physics experiments, only three days were available for machine development. Consequently, all preparations and special tuning to provide the specific mode of operation had to be performed at the beginning of the time reserved for the respective experiment. The operation of the various modes was performed under the new LSA control system. The basic functions of the storage ring mode have been established with the LSA system in the past years. The LSA system can be operated very reliably now, but the response time with complex storage ring patterns is still slow and compromises fast and efficient tuning of the cycle and pattern parameters. The large flexibility of the LSA system provides powerful tools to adjust the storage ring cycle according to the experimental requirements, but as a result, it also requires significant effort and time to prepare the ring operation in an optimum way and regarding all details of the experiment sequence. During the operation it was evidenced, that the new control system allows storage and recall of settings in a simple and reliable way. This eases the recovery of settings after failures or planned interruptions. Over the whole beam time the new bunch to bucket synchronization, which is under development for FAIR, was employed routinely to synchronize extraction from SIS and injection into ESR. It worked without any difficulty and in a preliminary test it could be demonstrated, that it is also very stable and powerful for the longitudinal beam accumulation in the previously developed method of injection of a bunch at the unstable fixed point of the rf system operated at h=1.

The physics experiments used storage ring patterns which had been developed in previous years. Only the preparation of decelerated beam for HITRAP was demonstrated for the first time using the LSA control system.

The beam time started with an experiment requiring uranium beam which is slowly extracted after electron capture of stored ions with a dedicated septum magnet. Although the ESR operation could be started smoothly, various problems in the injector chain resulted in serious delay. Together with the time consuming tuning of the beam line between ESR and Cave A, the beam could not be delivered in time and this experiment had to be cancelled finally. Two subsequent experiments in the ESR were devoted to laser spectroscopy of the stored beam using a laser beam, which was overlapped with the ion beam in the electron cooler straight section. Laser spectroscopy of a $^{229}\mathrm{Th}^{89+}$ beam produced in a 10 mm thick beryllium target in the TE line between SIS and ESR was requested by the first experiment. The intensity of the stored secondary beam at an energy of 380 MeV/u was limited by the intensity of the primary uranium beam and the large beam emittance of the beam after the beryllium target. The large emittance cannot be matched to the ESR injection system. A second laser spectroscopic experiment used a bismuth beam from SIS. The required hydrogen-like beam was again produced in the beryllium target in the TE line. This allowed firstly the confirmation of a previously measured resonance in $^{209}\mathrm{Bi}^{82+}$ and secondly the measurement of the resonance in $^{208}\mathrm{Bi}^{82+}$. This is the first laser spectroscopic measurement of a rare isotope beam in a storage ring.

Various accepted FAIR Phase-0 experiments require decelerated highly charged ions, either stored in the ESR or fast extracted for further deceleration in CRYRING@ESR or HITRAP. The lowest requested energy to date is the decelerated ion beam for HITRAP which has to be extracted with a precisely defined energy of 4 MeV/u. The cycle is similar to the production of decelerated ions for transfer to CRYRING@ESR. The integration of electron cooling of the decelerated beam as well the creation of a single bunch with the barrier bucket system operated at the very low frequency of 257 kHz before fast extraction was successfully commissioned with the new LSA control system. The bunching allows compression of the beam into a single bunch of less than 1 μs length which is favorable for efficient capture in the trap. The energy of the extracted beam needs to be matched with a precision of ± 0.1% to the design input energy of the linac. This year the main goal of this beam time period was recommissioning of the HITRAP linac and preparation for capture of decelerated ions in the trap. Stable operation and beam conditions of the fast extracted beam were achieved over the full period of more than a week. Also the deceleration of highly charged ions for transfer to and use in CRYRING@ESR was successfully continued. Presently fast extraction at an energy of 10 MeV/u is favored for CRYRING@ESR, as the beam lifetime of the decelerated highly charged ions in the ESR is not satisfactory and lower extraction energies would increase the losses during the deceleration cycle in the ESR. The deceleration process is very stable and for low beam intensity (below 1×10^7 ions) losses are close to the detection limited. Increasing losses are observed for higher intensities, but detailed studies of the reason for the loss increase with intensity were not possible due to a lack of machine development time. Such studies would be supported by improvements in beam diagnostics. Measurements of beam orbit and tune are now available over the whole deceleration cycle. In the final experiment of this year the internal gas jet target was operated with hydrogen at a very stable density of

5×10^{13} cm^{-2} to study the reaction of a bare $^{208}Pb^{82+}$ beam injected at 275 MeV/u and decelerated to energies of 30, 36 and 42 MeV/u. Starting from 1×10^8 injected $^{208}Pb^{82+}$ ions 5×10^7 decelerated ions were readily and reliably delivered to the experiment. Operation was quite stable and the integrated luminosity delivered to the experiment was even higher than requested in the proposal.

After the end of the beam time the shutdown period started at the beginning of July. In the scheduled shutdown period of about 16 months various defects will be remediated. Highest priority is the repair of a short to ground of the drift tube of the electron cooling system, which is an essential device for experiments which want to change the electron energy in the millisecond range. After a fast start this activity had to be stopped due to the discovery of thermal insulating material containing asbestos. The further disassembly is only permitted following special procedures and supervised by certified companies. The required permission to continue work under very strict rules was granted, but the organization of external support is still ongoing at the end of the year. The continuation of the disassembly and repair of the electron cooling device is expected beginning of 2023.

Over the years various problems occurred in the stochastic cooling kicker system installed in one of the ESR quadrupole magnets. For repair the quadrupole magnet had to be disassembled, the vacuum chamber was taken out and the kicker electrodes were dismounted and repair of the electrodes is ongoing.

Another problem, addressed in the current shutdown, are water leaks in the pole face windings installed in one main dipole magnet. For exchange of the pole face windings the more than 6 m long dipole vacuum chamber was dismounted to have access to the pole face windings. As spare coil will be installed to replace the leaky coil. The work in the southern arc of the ESR will continue into the first half of 2023.

As for the various activities the vacuum system in both arcs of the ESR has to vented the old sputter ions pumps will be replaced in both arc sections with new ones. It is expected, that the operation of the new pumps will mitigate the problem of relatively high vacuum pressure which is evidenced by short lifetime of low energy beams stored in the ESR.

9.7 CRYRING@ESR operation and development

Authors: Frank Herfurth, Claude Krantz, Zoran Andelkovic, Ingrid Kraus

The low energy storage ring CRYRING@ESR has seen its third year of routine operation. In 2022, it served three FAIR Phase-0 experiments with beams from the ESR ($^{197}\text{Au}^{78+}$) and from the local injector ($^{16}\text{O}^{2+}$, $^{2}\text{H}^{+}$ and $^{7}\text{Li}^{+}$). About $3\cdot10^{6}$ Au^{78+} ions were injected from the ESR at 10 MeV/nucleon, decelerated down to 3 MeV/nucleon, cooled and then extracted to irradiate a surface. The same beam, Au^{78+}, was also used to characterize the internal gas target in preparation of G-PAC experiments in the coming beam time periods. The beams from the local injector were used for dielectronic recombination (DR) experiments and machine development.

Already end of 2021, the aging ECR ion source (over 30 years old), used to produce ions for the local injector, broke. The plasma chamber developed a leak between the cooling circuit and the plasma volume and was disassembled. The permanent magnet arrangement was found defective too. While a new magnet system and plasma chamber are produced, another, smaller, but also aging permanent magnet system ECR was installed to provide the requested Ne^{3+} ion beam. The microwave generator for this broke in March 2022 which forced us to change back to the MINIS, a hot cathode ion source. A number of furnaces filled with lithium salt have been prepared to test the production of Li^{+} ions. Coincidentally, the singly charged lithium ion beam produced in the first tests could also be delivered to a DR experiment for a first run. However, the lithium beam requires much more dedicated development since injection inefficiency and operational instability both need improving compared to the makeshift first run.

A number of shifts of storage ring operation was also in 2022 dedicated to accelerator development and machine experiments. Besides an experiment to investigate the functioning of the new bunch-to-bucket system to synchronize the RF and extraction/injection systems of ESR and CRYRING@ESR, the proper functioning of the compensation solenoid was investigated closely. Further tests concerned chromaticity correction and the stability diagram in a larger area of tune values.

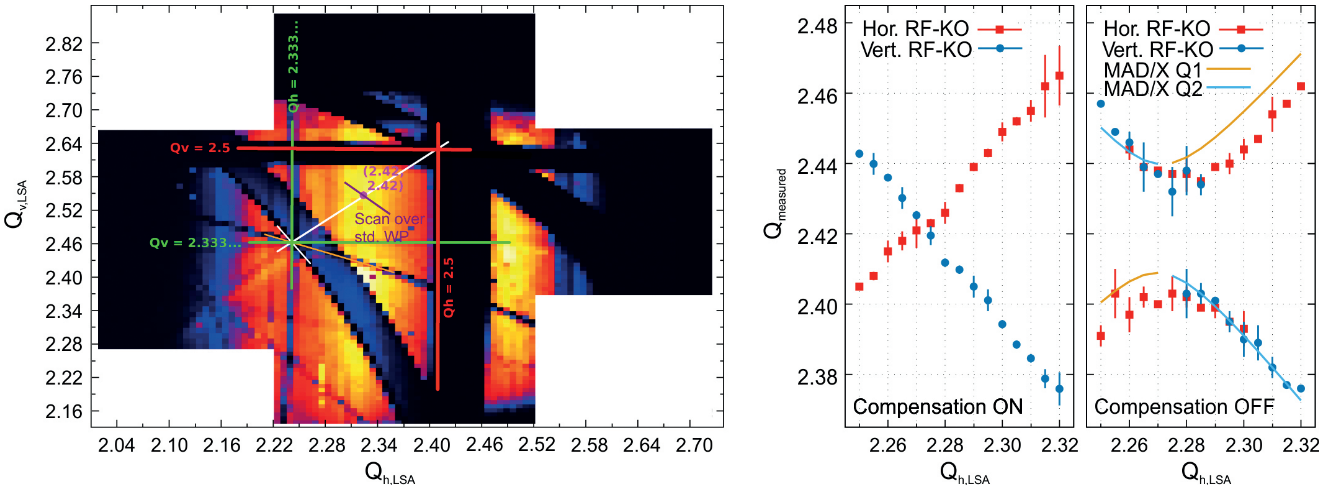

Figure 61. Stability diagram and tune measurements. The left part shows the measured beam intensity color coded versus the set horizontal and vertical tune values (Qh,LSA and Qv,LSA). Indicated by colored lines are tune resonances that also allow for a recalibration of set versus measured tune. The standard working point (measured tune values 2.42) is also indicated along with a line indicating the tune variation (scan) used for the measurements in the right-hand part of the image. The right-hand part shows two diagrams of horizontal (red squares) and vertical (blue dots) tunes measured using radio frequency knock out (RF-KO) versus set horizontal tune. When the coupling is not compensated (right most plot, Comp. OFF) the coupling prevents tune values close to the standard working point (2.42,2.42). In the rightmost figure MAD/X calculations support the data and indicate good understanding of the magnetic fields.

The compensation solenoid is designed to cancel the coupling action of the solenoid field in the electron cooler region. The solenoidal field required to guide the electrons along the ion beam axis in the electron cooler leads to coupled ion motion in the transversal planes, enabling energy transfer between the radial and vertical components of betatron oscillation in the storage ring. To cancel this mixing, a solenoid with inverted polarity but electrically in series with the electron cooler solenoid is installed in ring section 11. The machine experiment in 2022 was designed to measure the effect and hence the strength of coupling with and without the compensation solenoid. The main results are summarized in Figure 61. Betatron coupling is completely canceled when using the compensation solenoid, as demonstrated by the possibility to set any combination of horizontal and vertical tunes. Without compensation, coupling prevents the horizontal and vertical betatron frequencies to assume identical values, even given suitable quadrupole strengths. Despite this clear observation of the predicted coupling effect on the tunes near the standard working point of (2.42,2.42), no related deterioration of beam intensity, stability or emittance was detected in operation without the compensation solenoid.

Further investigations measured and reestablished proper chromaticity correction using the sextupole magnets. Also depicted in Figure 61 is the stability diagram over a large area using the final settings, i.e. including proper chromaticity correction and the compensation solenoid. The designed working point, which is 2.42 in both dimensions, is marked. The figure shows an offset between the tune model used to calculate the currents in the quadrupoles and the measured tune. From earlier experiments, it is known, that this also depends on further parameters like beam energy, intensity and bunching. Hence, more measurements with expanded parameter space are needed in order to reach a refined model.

In July 2022, an extended shutdown started. It will last until September 2023 and is used to repair and improve the vacuum system of the electron cooler, to improve on the beam instrumentation for injection and to rebuild the ECR ion source. Since the electron cooler has to be dismantled almost completely for this, the occasion will be used to equip it with electron beam clearing electrodes and a set of drift tubes to improve control over the electron beam energy in the cooling region.

9.8 Deceleration of ions at HITRAP

Authors: Zoran Andelkovic, Frank Herfurth, Nils Stallkamp (Goethe Universität Frankfurt), Simon Rausch, Max Horst (Technische Universität Darmstadt)

The heavy ion decelerator and trap HITRAP aims to provide low-energy highly charged ions (HCI) to various precision experiments [1]. This is achieved either by deceleration of ions produced by the GSI accelerator complex, or by local HCI production in an electron beam ion trap (EBIT). In that regards, HITRAP exhibits three distinct groups of activities:

Accelerator facility

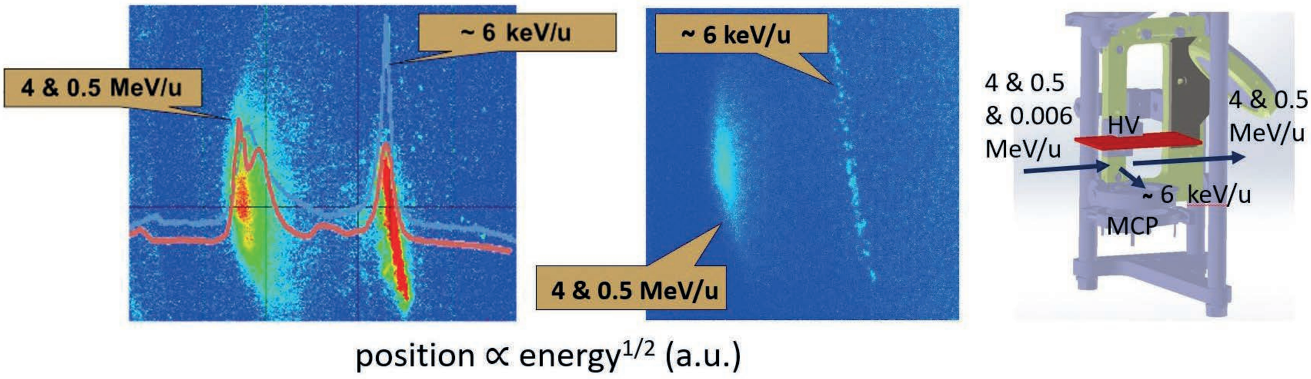

Figure 62. Image from the HITRAP energy analyzer, showing the ions decelerated by the RFQ in 2014 (left hand side) and in 2022 (center). After the RFQ the beam energies are separated with an electrostatic deflector for further optimization of the decelerated ions (right hand side).

The accelerator facility, comprising several radio-frequency (RF) stages and corresponding instrumentation for in-flight ion beam deceleration, has been in standby for almost eight years up to 2022, mostly due to low beam availability during the construction of FAIR and lack of local manpower. The single beam time in this year was used for recommissioning, for the upgrade to the FAIR control system, for bringing the diagnostics to FAIR standards and to train new personnel after the long pause. After four days of beam preparation from the ion source to the extraction from the ESR, some 10^7 particles of Ni^{28+} have reached HITRAP with a delivery rate of about one shot per 35 seconds. After fine-tuning the energy of the extracted ion bunch to exactly 4.024 MeV/u, the beam quickly showed that the IH structure, as the first deceleration stage, was ridden by stability problems. It took an unusually long time of seven days to bring it into proper operation, including transmitter repair and venting to readjust the HF coupling unit. The remaining two days were used for optimization, separation of decelerated and non-decelerated ion beam components and finally the RFQ as the last deceleration stage to 6 keV/u. A comparison of the results achieved in 2014 and of the recommissioning in 2022 can be seen in Figure 62. The difference in brightness comes mostly from different detector settings, however the relative positions are identical.

Although the ultimate goal of reaching the cooling trap and preparing the ion beam for further transport remains a task for future beam times, this year's positive recommissioning result gives reason for optimism. It also underlines how important regular operation intervals are for any accelerator, especially if low delivery rates are involved.

Low-energy ion transport

Low-energy ion transport at around 6 keV/u guides the decelerated ions from the RFQ into the cooling trap. This is a multi-staged process, involving multiple single-shot energy analyzers as shown in Figure 62, electrostatic beam focusing elements and differential pumping barriers. Several tasks were completed in the preparation period for this year's beam time. The local, LabVIEW-based control system was consolidated with a graphical user interface and expanded to operate the diagnostic drives. The movable diaphragms after the RFQ were repaired for precise beam alignment. The diagnostic stations were modified to separate the decelerated beam from the fast components and tested with the local injector of CRYRING@ESR. Also a vacuum baking system was reinstalled to improve the residual gas pressure in the vicinity of the Penning trap. These activities continue in the shutdown period of the GSI accelerator complex. On the other hand, beam delivery from the local EBIT has been in regular operation for about 10 years, serving both the cooling trap and experiments with light HCI. Beside regular hardware maintenance of vacuum equipment and power supplies, also preparations for the transition of the control system from LabVIEW to FAIR CS are ongoing. These include retrofitting device controls, an upgrade of diagnostic elements, physics model integration as well on the design of a new motorization system for 12 diagnostic stations and their control units.

Cooling of trapped ions

Cooling of trapped ions, comprising a Penning trap in a superconducting magnet, remains the most challenging part of the project. The trap is designed to capture HCI and enable energy transfer to simultaneously stored electrons, which dissipate it by emitting synchrotron radiation. Meanwhile this process has been consolidated up to a point where both particle types are stored together on a regular basis. However, so far the energy transfer is observed only by its influence on the electron plasma and not vice versa [2]. Efforts to monitor and tune the interaction process in more detail are ongoing with a design of a new imaging system close to the electron plasma. The shorter imaging distance reduces the magnifying effect of the magnetic field gradient to a factor of 5, compared to the currently available factor of 70 which exceeds the available detector surface.

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9.9 High-energy beam transfer lines - status and upgrades

Authors: Christoph Hessler, Oksana Geithner, Petra Schütt

Operation highlights

The high-energy transfer lines (HEST) have delivered a wide range of different beams from SIS18 to a large number of experiments during beam time 2022. One of these experiments was the HADES experiment operated with a high-energy proton beam. The operating conditions were very challenging, because the beam intensity had to be limited to 10^6 p/s due to the delicate electronics of the detector. However, such a low intensity proton beam is not detectable with standard HEST diagnostics. Furthermore, a relatively small focal spot size with a beam as parallel as possible was required. To overcome these difficulties several improvements have been realized in HEST [1], which resulted in a successful delivery of the beam to the experiment.

Another important step was made for the operation of the ESR-CRYRING and ESR-HTA beamlines: The reason for the long-lasting discrepancy of theoretical and actually needed deflection angles in the dipole magnets was found. This issue was caused by faulty scaling of the magnet currents in the controller boards of the power converters. After fixing the problem, a good agreement of theoretical and actual deflection angles was achieved and a good orbit control of the beam towards CRYRING could be established. However, there is still another issue: Both beamlines suffer from a cross talk with the beamline towards HTC/D. If the dipole magnet GTV1MU2 in the beamline towards HTC/D is switched off - as it is needed to access cave C - the beam towards HTA/CRYRING changes position. The most likely reason for this behavior is that the low rigidity beam is within reach of the magnetic field of GTV1MU2.

Machine studies

Several machine experiments have been performed in HEST during beam time 2022. The goal of one machine study was to determine the Twiss parameters and dispersion values at the ESR extraction point as well as the transverse emittance of the beam fast extracted from the ESR towards CRYRING. For this purpose, dispersion measurements and quadrupole scans have been carried out in the ESR-CRYRING beamline. The data analysis is on-going. Preliminary results show that the previously assumed dispersion value at the start of the beamline has to be corrected in the optics model.

The goal of a HADES machine study was to verify the suitability of a new beam optics setting for the beam line for a future HADES pion run. During the last HADES pion run in 2014 high radiation dose levels have been observed due to beam losses of high-intensity beams in the TH2/TH3 area. The maximum dose level was observed near dipole magnet GTH3MU1 [2]. Such high radiation dose levels must be avoided in future pion runs, therefore several improvements have been realized in the HADES beam line during recent years:

- Installation of beam loss monitors.
- Increased aperture of some vacuum chambers at critical positions.
- Development of a new beam optics setting for pion production.

Another aim of this study was to check whether the experiment requirements for the beam intensity are achievable with these improvements without exceeding the allowed radiation limits. During the experiment, pions were successfully produced, although it was not possible to measure their intensity. With the new optics setting the losses near GTH3MU1 disappeared, however, losses appeared further upstream. Consequently, the beam widening had to be reduced, which might have a negative impact on the spot size on the pion target and the pion production rate. The required primary beam intensity could not be reached during this experiment, most likely because of the following issues:

- SIS18 electrostatic extraction septum was damaged, which decreased the extraction efficiency down to 30%. Its repair is mandatory in order to reach the required extraction efficiency of >80%.
- BB6 buncher at UNILAC was not operational.

Therefore, it is not clear if the losses near GTH3MU1 would still be low with nominal primary beam intensity. It is planned to repeat this machine experiment after the repair of the electrostatic septum

Upgrades

In HEST several upgrades are on-going. On the software side, the online-model application "Benno" is being continuously upgraded with new features. Recently, functions for steering the beam onto the target and onto the beam axis have been added, as well as a function for tuning the longitudinal focus position in the target area and a function for calculation of the initial beam position and angles at the start of the beamline. These new functions have been routinely used by the operators during beam time 2022.

On the hardware side, additional beam loss monitors (BLM) have been produced and the corresponding cables installed. The completion of the BLM installation is expected in the current shutdown.

Furthermore, the currently unused beam position monitors (BPM) in the SIS18-ESR beamline have been re-cabled and it is planned to put them back in service, using DAQ modules borrowed from FAIR. The BPMs should be available during the next beam time.

The ion pumps in HEST are aging and need to be replaced in the foreseeable future. Therefore a campaign has been started to procure replacement pumps and to replace all 55 ion pumps in HEST during the coming years. To optimize the personnel resources, it is aimed for installing the pumps in sectors when the vacuum system needs to be opened anyway for other reasons. So far, 21 ion pumps have been procured and 12 of them have been installed.

The most important upgrade project in HEST for the coming years will be the signal digitization of currently analog beam diagnostic devices. The project consists of the upgrade of 15 analog cameras to digital cameras and the digitization of the analog signals of 4 fast current transformers (FCT). This upgrade is essential for operation of the HEST beam lines from the new FAIR Control Center (FCC), since cables for analog signals will not be available in the FCC.

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9.10 Long shutdown 2022/2023 – activities and progress

Authors: Miriam Klich, Petra Schütt, Max Müller

Boundary conditions

This year's shutdown started on July 1st, 2022 directly after the user beamtime was finished with one of the framework giving activities, the renewal of the medium voltage (MV) switchgear =AA. The boundary conditions for this shutdown were given by three main tasks, which have been challenging due to their duration, impact or complexity. Since many buildings are affected by the electricity shutdown, the renewal of the MV switchgear has a substantial impact. The second framework giving activity comprises renovation, installation and commissioning of the ventilation system 16 (LA16) and the renovation of the roof of the supply rooms (VR). The third activity is the complex repair of the ESR cooler.

The electricity shutdown for the renewal of the MV switchgear =AA affects almost each building adjacent to the UNILAC tunnel. For this it was decided to split measure into three subtasks, starting with subtask 1 right after the user beamtime was finished. For each step provisional power delivery were provided; the first two steps were successfully finalized by the end of September 2022. The third step started on December 9th, 2022 with an expected duration until mid January 2023.

The activities for the refurbishment of the LA16 and VR roof were planned in close coordination with the UNILAC RF department due to the specific local conditions. The old ventilation ducts were dismantled after protective measures in the RF gallery have been conducted. A weather protection cover was set up during the renovation of the VR roof. Most of the construction work will be finished by the end of 2022, the commissioning of the LA16 will start by the beginning of 2023.

The complex repair of the ESR cooler was scheduled for a period of 9 month, but it is associated with various uncertainties: Many different expert groups are involved in the disassembly process, which includes an inventory, while also measuring and ordering the heating shirts. End of July 2022 after media infrastructure were dismantled, asbestos contamination was observed and the activities were immediately stopped. Appropriate official permission had to be obtained for handling these contaminations and a disposal company must be found. The goal is to continue the repair work in January 2023.

Machine activities

The update of the vacuum control system in the transfer channel (TK) is in progress, which includes the assembly of cables, the installation of control racks, the integration of the new system and, if necessary, the exchange of vacuum pumps. The exchange of an internal Alvarez 1-drift tube and the repair of a vacuum leakage at Alvarez A2 started right after finishing the first step for the renewal of the MV switchgear =AA. The mechanical work for these two activities will be finished by the end of 2022. Due to the outdated documentation of the emergency stop system it is intended to continue the already started modernization in parallel to the electrical shutdowns for the MV switchgear =AA. Standard maintenance e.g. at secondary electron emission (SEM) grids or ion getter pumps takes place during the complete shutdown phase.

The activities at the SIS18 are influenced by the tasks of the civil construction. The time-consuming wall breakthroughs on GSI side for the connection to FAIR have been carried out. Parts of the area close to the SIS18 were handed over to FAIR at the end of November for three month to continue the FAIR activities for the connecting tunnel T101. A wall at the kicker room will be reinforced from both sides, for this the required material had to be transported into the SIS18 tunnel. Subsequently the SIS18 tasks could start. The focus is on the maintenance of the ionization profile monitor (IPM) and the repair of the electrostatic septum (E-septum), which finally started in December 2022 right after the cleaning of the SIS18-tunnel. The refurbishment of the target hall (TH) roof was made right above several parts of the SIS18 RF system. For this the activities could only be carried out under consideration of various RF tests. The renovation was finished at the end of 2022.

The main task at the ESR is the repair of the cooler, additionally in the south arc the repair of the stochastic cooling and the pole face windings of a dipole is ongoing. However, the final bake out will only take place after completion the repair of the cooler in 2023.

The cooler of the CRYRING is also going to be repaired, the activities are interrupted due to the delayed delivery of the heating shirts. Furthermore, a new ion source has been installed and will be commissioned at CRYRING-injector.

After successful recommissioning of HITRAP, further RF testing is ongoing.

The assembly of the accelerator cold-string for CW-LINAC-cryomodule 1 in Mainz is well advanced and the transport to GSI is scheduled for beginning of 2023.

The November-Dry-Run, dedicated for device tests, started with bumper and RF system checks at SIS18. During the second week, equipment was tested in the remaining accelerator facility. At UNILAC, dedicated ion source performance tests and tests of the new ion source application as well as sequence tests were performed. Tests of emittance measurement software with and without beam took place as well as a high power temperature check at the septum coil at the exit towards the experimental area. Furthermore at the ESR the power supply of the septum was tested and the control of multiple devices by the control system throughout the whole GSI-accelerator facility.

Outlook for 2023

The activities on the renewal of the MV switchgear will be finished in January 2023. The commissioning of the ventilation system will be completed by the end of August 2023. The repair and re-commissioning of the ESR cooler under the current conditions is scheduled for end of November 2023. The completion still involves some uncertainties, such as the delivery of the heating shirts and the duration of the reassembly of the cooler.

The work on the roots pump station for the pulsed hydrogen gas stripper in the UNILAC will start in March 2023, dependent on the successful execution of the factory acceptance test (FAT).

At the SIS18 a prototype of a cryogenic insert and a cavity for smoothing the spill structure will be installed in summer 2023.

It is planned to conduct an engineering run starting in November 2023 dedicated to machine tests and machine experiments. From May to July, the survey and alignment will take place. After net measurement of the whole facility, data will be evaluated, followed by adjustment of dedicated sections, if necessary. During data evaluation, the first of three Dry-Runs will take place, where the new operating system will be intensively tested. At the end of September until mid of October, a last Dry-Run as a final acceptance test is scheduled.

9.11 UNILAC shutdown activities 2022

Authors: Uwe Scheeler, Hartmut Vormann, Winfried Barth, Markus Vossberg

During the beam time in the first half of 2022 the shutdown preparation was ongoing with the fabrication of drift tube no. 10 of Alvarez tank 1 (UA1BA1) and the detailed planning of resources for the different measures. After the exchange of a vacuum seal in Alvarez 2 (UA2BA2) at the end of 2021 the achieved vacuum pressure was not as good as expected, thus a careful maintenance program for this cavity was scheduled. In July the IH Cavity of the High Charge State Injector (UN5BI1) was opened to investigate the dimensions of the first drift tube in order to procure a spare part of the defect quadrupole triplet lens. At the transfer channel to the SIS18 the RF power transmission line for rebuncher TK4BB11 showed a high RF resistance. After the dismantling water was detected inside, the single pipe pieces had to be cleaned and the contacting connections were reworked.

The start of shutdown activities (mid of August) at the UNILAC tunnel was disturbed by unexpected break downs of the power grid while the emergency switch-off system was repaired. Therefore, the start of leak search at Alvarez tank 2 was delayed. The cavity was dismantled, the sealing of the cavity plate as well as the first cavity section (see Figure 63) were exchanged in the second half of September. The following vacuum commissioning was long-lasting, in particular the exchange of the fore-vacuum hoses due to the delayed delivery of the needed spare parts.

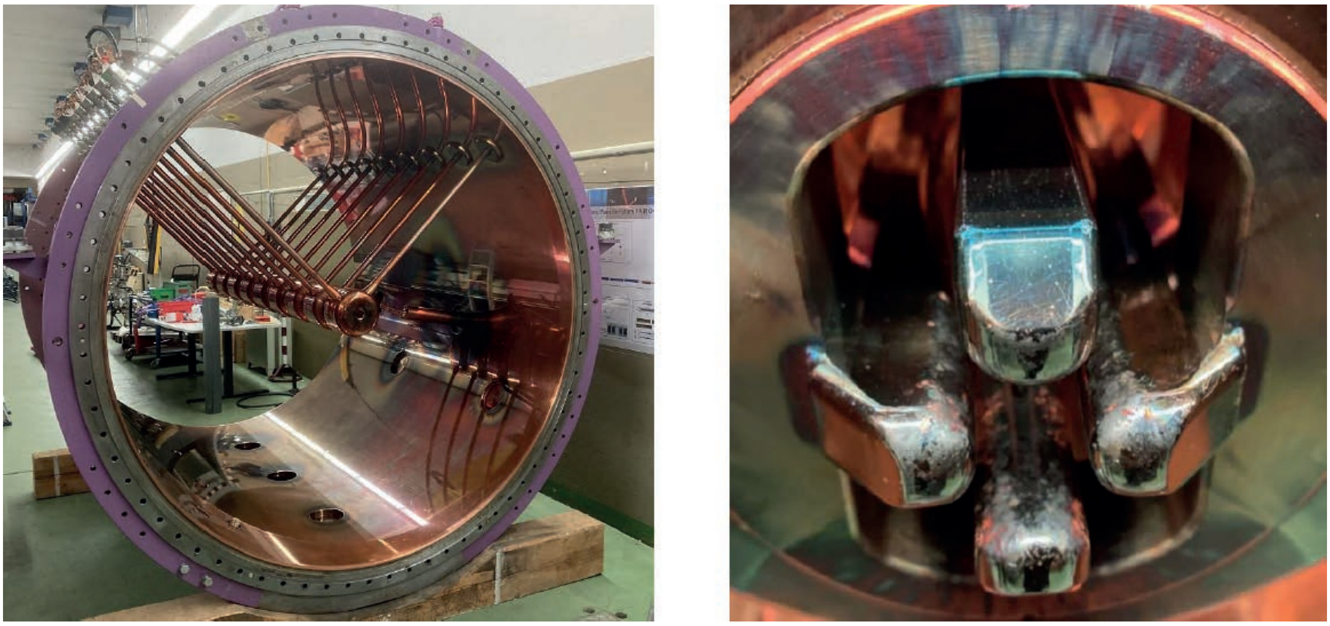

Figure 63. Dismantled section 1 of Alvarez tank 2 (left); eroded Superlens electrodes at the beam entrance (right)

The Superlens (UH3BB1) performance at the High Current Injector degraded further during beam time 2022. The fabrication of four new rods had been started in advance and was finished in May 2022. At the end of the beam time it was decided to exchange the rods after 20 years of operation (Figure 63). In November the cage with the carrier rings and the four rods was disassembled and completely dismantled. The carrier rings are going to be reworked concerning degraded surface quality, new rods have already been fabricated - the next step is the reassembly of all things.

During the beam time several profile grids were destroyed caused by high beam power, in particular in the transfer channel (TK). During trouble shooting it was noticed, that the profile grid protection system was not properly working for the TK straight forward beam line, which was extensively used for high intensity Uranium beam operation. A detailed check of the protection system function revealed a software error. For high intensities the beam pulse length was not shortened in order to prevent any damage. Meanwhile this problem is solved.

As a long-term measure the vacuum control system in the TK is being upgraded to the new UNILAC standard. Recently the hardware installation was finished, whereas the software part still has to be performed.

A spare part related issue is the procurement and fabrication of three new magnet coils for the so called tunnel septum (UT2MU2) in front of the beam transport system of the UNILAC experimental hall. The call for tender started in February, in May the order could be placed. A lot of coordination effort was necessary to update the 40 years old drawings of the magnet with the real dimensions. Meanwhile the first pair of coils for one septum magnet is almost assembled and delivered. The exchange of the defect septum will start after a final check of the vacuum capability.

9.12 Division operation infrastructure support

Authors: Gertrud Walter, Markus Romig, Stephan Teich, Jens Holluba, Tanja Dettinger, Mathias Henke

In 2022 different support activities have been carried out by the Operation Infrastructure Support OIS, i.e. by the departments of technology laboratory and mechanics & metalworking. Both departments continued their strong collaborations e.g. of using special manufacturing, welding, and galvanic Cu plating technologies. Special examples for these ongoing activities are the construction of different parts and devices for the FAIR accelerators including the Alvarez upgrade at the UNILAC. In addition, a variety of experimental setups have been supported during FAIR phase 0 beam time 2022 and in preparation of future beam times

Mechanical workshop and metalworking

The Department Mechanical Workshop and Metalworking is continuously supporting the existing and FAIR accelerators as well as all experiments by manufacturing technical. This includes all related manufacturing procedures and their development, e.g. the use of a variety of welding processes especially for superconducting magnets for FAIR under very limited space conditions.

Technology laboratory

The Department Technology Laboratory supports manufacturing processes by related R&D procedures in advance, e.g. for soldering or heat treatment, and by measures for quality assurance such as mechanical precision measurements, leak testing, etc. In addition, the department operates our Galvanic workshop for high-quality Cu plating of large-scale accelerator structures.

Figure 64. Left to right side: a: Adjustable magnet feet for FAIR. b: Galvanic workshop refurbishment – new large scale galvanic vessels for electroplating the big Alvarez tank sections. c: Solid Cu drift tube of existing Alvarez after soldering. The small figure shows the grinding pattern of the soldering joint.

Activities in 2022

The following projects/activities have been supported by the departments of OIS:

- A half drift tube for the Alvarez upgrade has been fabricated.
- In addition, a solid copper spare drift tube for the existing Alvarez accelerator has been constructed as spare parts are no longer available. The available technical documentation was not complete. Therefore the soldering process has been optimized in a systematic experimental study using our vacuum soldering oven. A successfully soldered drift tube is shown in Figure 64.
- The series of cutting and welding of flanges of 108 SIS100 magnetic dipole beam pipe vacuum chambers has been completed.
- Complicated welding tasks for adjustable feet for different FAIR magnets have been performed (see Figure 64 a).
- For the ECR ion source a prototype plasma chamber has been fabricated to minimize welding distortions during different construction steps with focus on CAD/CAM machine programming.
- FEM analysis support for different projects was ongoing.

In parallel to the technical support of different projects, the Galvanic workshop retrofitting has made significant progress. The construction and technical installation works are close to completion in order to start the commissioning in Q2 2023 (see Figure 64 b).

9.13 UNILAC machine investigations

Authors: Winfried Barth, Uwe Scheeler, Hartmut Vormann, Maksym-Miski-Oglu, Markus Vossberg, Stepan Yaramyshev

One of the crucial quantities at a fixed beam intensity to characterize the high-current capability of a synchrotron injector is the horizontal beam emittance. In order to determine the behavior of the UNILAC for heavy ion beams, in three consecutive years high intensity Bismuth and Uranium beams were used in several machine investigation runs for the first time to measure the transverse beam emittance at five selected measurement positions along the complete UNILAC.

The different measurement locations are the LEBT-section (Bi^{4+}, U^{4+}), in front of the HSI, behind the Hydrogen-gas stripper and charge separation system at 1.4 MeV/u (Bi^{26+}, U^{28+}), in front of the Alvarez section and for the same charge state behind the poststripper, in the middle of the 160 m long transfer channel to the SIS18 (section TK5) and at its end (section TK8). [1]

The corresponding normalized emittance values show the effect of asymmetric emittance growth, which occurs at high intensities, especially when using the hydrogen stripper. This leads to an increase in vertical emittance whereas the horizontal size decreases. This effect can be detected behind the gas stripper along the complete UNILAC; at the end of the transfer channel for Bismuth beam an approximately three and a half times smaller horizontal emittance was measured compared to the vertical value.

For efficient beam injection into the SIS18, as desired, a very small horizontal emittance of 0.42 mm x mrad (4 x rms, 90%, normalized) is available in order to provide for a sufficient number of (multi) turns. From the LEBT to TK9, no net emittance growth could be measured in the horizontal direction, whereas the vertical emittance increases by about a factor of 5. However, it must be considered that particle losses of more than 40% occurred along poststripper and TK, which may distort the emittance growth balance.

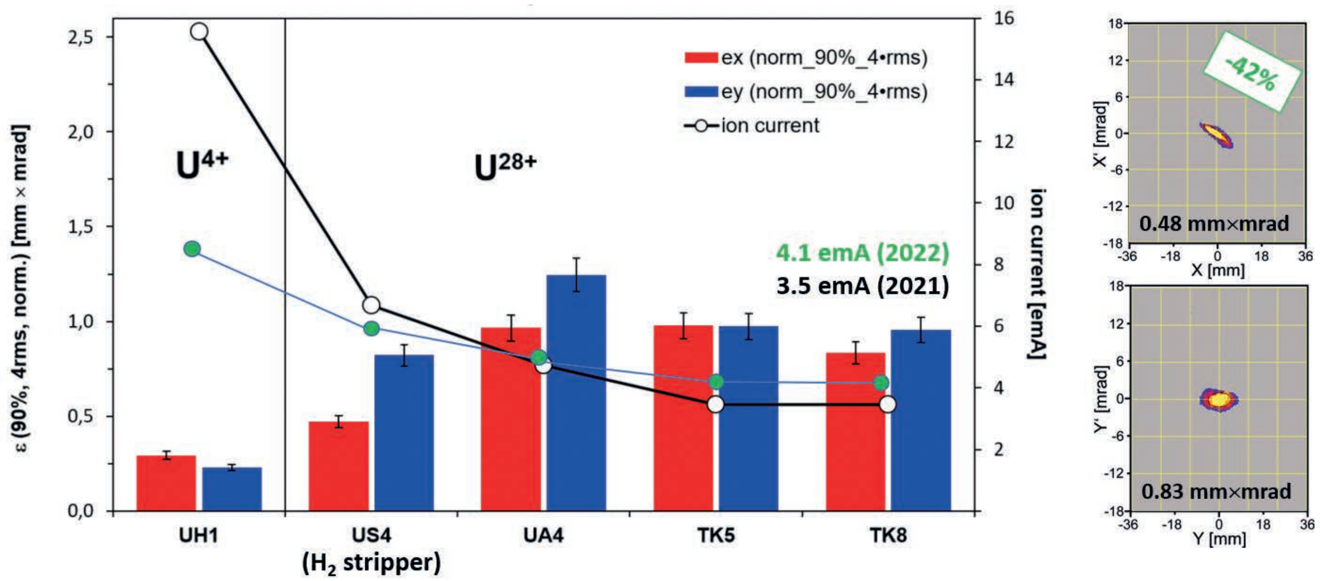

Figure 65. Measured high current Uranium beam emittance development along UNILAC and transfer line (left) and corresponding U^{28+}-measurement (2022) at SIS18-injection, with 42 % reduced horizontal beam emittance.

The complementary data for Uranium beam measured in the 2022 machine campaign are summarized in Figure 65. The effect of asymmetric emittance growth/reduction behavior has also been demonstrated for Uranium beams. With practically identical loss scenario in postripper and TK, however, the effect is less pronounced. After changing the wrong polarity of the quadrupole quartet in front of the HSI-RFQ beam transmission could be increased, while beam emittance growth has been significantly reduced compared to the 2021 campaign. At the end of the transfer line to SIS18 a 90% emittance (4 x rms) of 0.48 mm x mrad has been obtained at a beam current of 4.1 emA ($9.1 \cdot 10^{10}$ particles/100μs). Through horizontal collimation (≤4.0mm·mrad), the number of Uranium particles in this phase space area is sufficient to fill the SIS18 by more than 40% of the space charge limit [1].

A significant improvement in beam brilliance was achieved by using the pulsed hydrogen stripper, as well as the quadrupole setting with changed polarity. Further improvements in brilliance can be expected from the planned upgrade measures, in particular on the high-current injector linac.

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9.14 Progress report on the UNILAC pulsed gas stripper

Authors: Peter Gerhard, Michael Maier

High intensity heavy ion beams are a main constituent of the FAIR research programme. 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 8.5. An effort has been made to enhance the stripping by introducing hydrogen instead of nitrogen as stripping target, thereby increasing the stripping efficiency, which is on the order of 0.14 for heavy ions, by up to 60% [1, 2]. The focus of the project is now on transforming the experimental setup into a system suitable for regular operation.

In 2022 the main effort was on the finalisation of the technical and safety concept, which had been thoroughly revised last year and was awaiting final risk assessment. In collaboration with the expert safety consulting company Consilab, the technical and safety concept was approved with some modifications. During this process some of the originally planned safety measures were found to be unnecessary, resulting in a minor reduction of complexity and cost. The explosion safety document, relevant for later operation, compiled. Based on the design now being approved, the remaining parts necessary for the gas stripper facility will be specified and procured.

Figure 66. Left: Setup for the safety tests in the test bunker. The vacuum chamber containing the stripper setup was equipped with a gas inlet manifold for H_2 and dry air, fast and slow pressure sensors and a thermocouple to detect any ignition. Right: The existing three-stage pumping station to be replaced for explosion safety. It comprises two staged roots pumps and two single-stage rotary vane pumps in parallel as the third stage.

At the test stand the preparation of safety tests of the pulsed valves were continued early this year. A single set of operating parameters for the injection valves was elaborated, suitable for the different requirements of long and short pulse operation with different gases and pressures. At the same time, the backup cooling of the valves by thermal conduction using flexible copper strands was verified. The upgrades applied to the test stand equipment last year facilitated an efficient and successful preparation of the safety tests. Additional safety margins for the electrical parameters were defined for the safety testing, which took place late in 2022 at the testing grounds of the accredited expert company for explosion safety IBExU. The gas stripper setup was placed in a test bunker (Figure 66 left). The chamber was filled with most easily ignitable H_2-air-mixture at different pressures. Then the two valves of the stripper setup were run 2 h for each pressure, applying worst case operating parameters including safety margins without any gas flow through the valve, thereby creating maximal electrical, mechanical and thermal stress on the valve. No ignition occurred, confirming that the valves can be operated safely in the gas stripper with hydrogen.

As usual in the last years, the current prototype was operated for a development beam time. Its main purpose was to verify the operating parameters for the injection valves, specified earlier on the test stand, with beam. This was achieved by a minor adaptation, which was attributed to the much longer cables connecting the valves to the controller at the accelerator. The second objective was to compare operation with and without a large gas buffer volume right in front of the injection valves. If this buffer volume was not needed the reduced amount of hydrogen in the system made a valve failure much less hazardous. The experiments showed, that it can be left out with negligible effect on the stripping performance even for long pulses. The remaining operation time with H_2 was used to serve a machine experiment beam time at UNILAC and SIS18. In total, the pulsed gas stripper was operated smoothly and reliably for seven days, thanks to the improvements performed recently.

As the next major step towards completion of the gas stripper facility, the call for tender for an explosion safe roots pumping station was published early this year. The existing three-stage pumping station to be replaced is shown in Figure 66 right, comprising two staged roots pumps and two single-stage rotary vane pumps in parallel as the third stage. This setup is replicated and provides for a pumping speed of 9000 m^3/h for hydrogen. The order was placed in July with Pfeiffer Vacuum. Finalisation of the mechanical, electrical and software design took until end of 2022. Acceptance tests, delivery, installation and commissioning are planned for the first half of 2023. Further progress was also made on the gas alarm system. The system layout and functionality was developed and specified. Key components like the gas sensors were ordered and already delivered for installation next year. Commissioning for regular operation is aimed for in 2025.

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9.15 Starting series production of the new UNILAC post-stripper DTL Alvarez 2.0

Authors: Lars Groening, Sascha Mickat, Xiaonan Du, Manuel Heilmann, Michael Kaiser, Michael Maier, Anna Rubin, Chen Xiao

The existing post-stripper drift tube linac (DTL) of the UNILAC suffers from aging and increased failure rate. Additionally, its design does not meet the FAIR requirements. The new DTL Alvarez 2.0 will replace this section [PSU Dept., Technical design report of the Alvarez 2.0 post-stripper DTL (V13b) for the UNILAC, ALV2_note_20210915, GSI (2021)].

Highlights in 2022

Fall of 2021 saw successful operation of a dedicated first-of-series (FoS) cavity section (without beam) at RF-parameters in excess of the aims imposed by the DTL as FAIR injector [Heilmann, M. et al. RF-commissioning of the first-of-series cavity section of the Alvarez 2.0 at GSI, LINAC2022 Conf.]. In parallel to preparation of these tests, tendering of series components has been followed up. It aimed for coincidence of successful completion of FoS testing with readiness to order series production. In early 2022, the 25 cavity section mantles and 10 cavity end plates have been ordered, as the DTL comprises five cavities of five sections each and each cavity has two end-plates. Albeit the difficult overall circumstances w.r.t. procurement of raw material in this year, costs and planned schedule agree to the initial project planning. The production of the five sections of the first cavity has been started in June.

Figure 67. Production of the five cavity section mantles forming the first cavity

A very critical issue is keeping the tight tolerances of the cavities inner radii of a tenth of a millimeter. The radii determine the RF-frequencies of the cavities. Rolling and welding of the mantle from a large single metal sheet is the first and simultaneously the most critical production step. For the time being, all mechanical tolerances have been met and presently ports and flanges are welded onto the section. Figure 67 illustrates the states of production as of November 2022 of the five sections of the first cavity. Interface assemblies to install the drift tubes have been produced. Figure 68 shows the ports for the drift tubes of the first section. The first cavity comprising five sections and two endplates shall be delivered in the first quarter of 2023.

Figure 68. Interface assemblies to be welded onto the cavity mantle; they serve to install the drift tubes

Many add-on parts have been ordered and are in production. Several components have been produced and delivered. Each cavity is equipped with a large port of about 600 mm in diameter to install the coupling loop for the incoming RF-power. Another port of same size serves as maintenance opening to allow for human access. The five flanges to provide for the RF-coupling as well as those to close the access ports have been produced and have been delivered in late 2022 (Figure 69). The delivery included two spares of each type.

The complete DTL will be equipped with 200 RF-tuners. Bodies for the static tuners have been produced to the maximum length. During low-level RF-tuning, the individual lengths will be determined and the bodies will be shortened accordingly. This tuning will be done through manually driven tuners, which have been delivered. High RF-power is coupled in by dedicated loops mounted onto a ceramic ground body each. The latter are under production and two of them per year will be delivered from 2023 to 2025. The forwarded and reflected RF-power per cavity are to be measured with two RF-pick-up probes per cavity, which have been delivered as well. Additionally, production of the 400 stem seals (incl. spares) has been started in Summer. These flexible seals allow for alignment of the drift tubes from outside.

A total of 177 drift tubes along the DTL provide for acceleration gaps and transverse focusing. Each drift tube houses one pulsed and cooled e.m. quadrupole magnet and is kept by two stems. Series production of drift tubes shall start after rigorous R&D, which was done successfully through prototyping of the shortest drift tube in 2021. A prototype of the longest drift tube has been ordered in Summer and the CDR has been approved in Fall.

Series production of the first 52 drift tubes and six spares (equivalent to the shortest tube) for the first cavity has been tendered in 2022. Negotiations with providers have been close to completion in December. The following table summarizes the current status of series production of Alvarez 2.0:

component	**# pieces**	**status**
Cavity sections / end plates	25 /10	first cavity under production
bodies for static tuners	200	delivered
bodies for RF-power loops	6	under production
RF-pick-up probes	30	delivered
manual tuners	40	delivered
alignment set-up for stems	400	tendering ongoing
stem seal flanges	400	25% delivered
drift tubes of first cavity	52+6	awarding

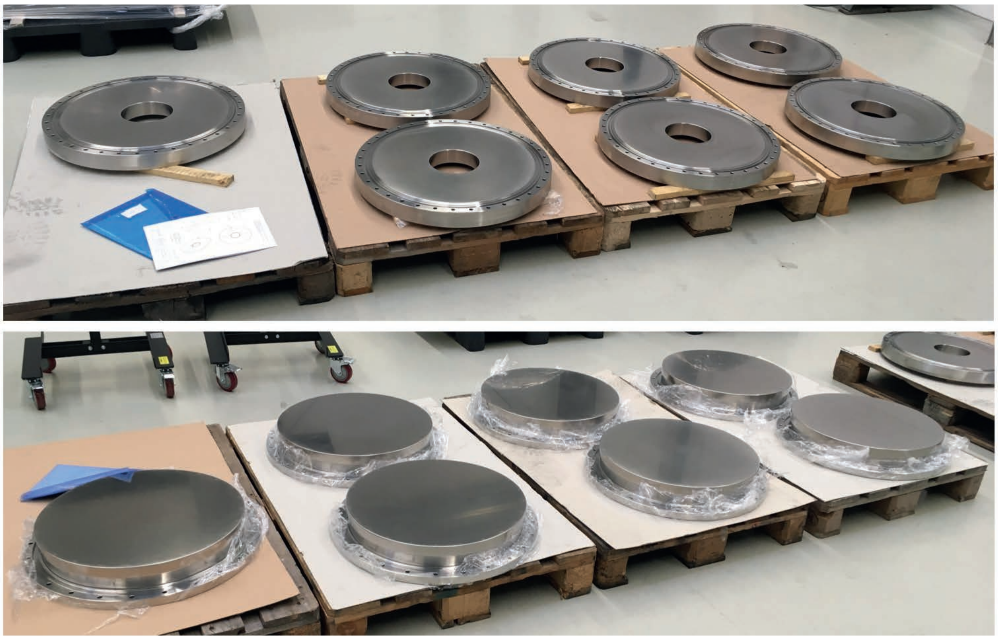

Figure 69. Flanges to provide for RF-coupling (upper) and to close the maintenance ports (lower)

Outlook for 2023

During next year, all sections of the first two cavities shall be delivered and accepted on-site. Copper plating of the sections shall start in Summer at GSI's on-site galvanic work shop. In order to increase efficiency of plating, the existing "Betriebshof" of GSI shall be re-furbished thus allowing for preparation of copper plating therein. This refurbishment implies considerable civil construction activities especially caused by change of the building's dedication from "storage" to "working place". Additionally, this refurbishment shall prepare the location to be used for cavity string preparation, as for instance testing, drift tube installation, and low-level RF-tuning.

Order for the drift tubes of the first cavity shall be placed in early 2023. Additionally, the tendering of the other drift tubes shall be started such that the order can be placed about one year later. In parallel, the prototyping of the longest drift tube shall be successfully concluded.

9.16 Further development of high current ion sources at GSI

Authors: Aleksey Adonin, Ralph Hollinger

The development program for high current ion sources in 2022 was carried out in two main directions: improvement of operational reliability and performance of existing ion species as well as development of new ion species for GSI and future FAIR experiments.

New setup for CH_3^+ operation

For the production of high intensity proton (H^+) and carbon (C^{x+}) ion beams at the UNILAC, a high current CH_3^+ molecular ion beam is used, provided by the MUCIS-1990 ion source from methane gas. MUCIS-1990 is a volume type gaseous ion source, frequently used in the past (10-30 years ago) for operation of a wide range of gases from H_2 to Kr [1]. Currently, the operation of light gases (from H_2 to Ar) is accomplished with the more compact and more simple CHORDIS ion source, while the operation of heavy gases (Kr and Xe) is realized with the more efficient MUCIS-2010 ion source. Thus, the MUCIS-1990 is basically used for molecular ion beams production, only.

Recently, there was only one exemplar of the MUCIS-1990 source. Therefore, to increase the reliability of CH_3^+ operation, a second exemplar of MUCIS-1990 has been constructed and successfully tested. Moreover, MUCIS-1990-II has a number of advantages compared with the first one. It is equipped with heat resistant permanent magnets with a field strength of up to 1.1 T, which create the multi-cusp magnetic field inside the plasma chamber. MUCIS-1990-II also has an improved external solenoid, realized with a double layer of a ø2 mm Cu-wire (as against a single layer of ø1.3 mm in the first exemplar), that allows higher magnetic fields by the same solenoid currents due to the increased number of turns.

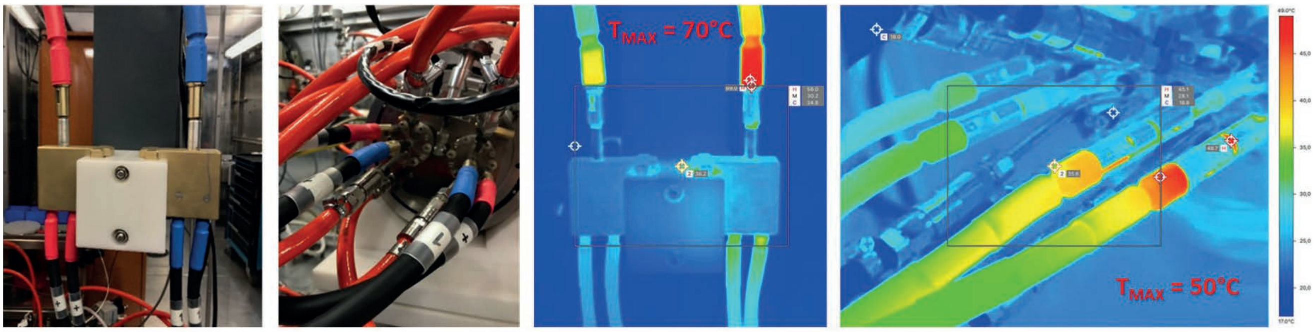

Figure 70. High current splitter for IS-filaments (left); temperature measurements of electrical connections after improvement at full power operation using a thermo-scanner (right).

As opposed to the other gaseous ion sources, CHORDIS and MUCIS-2010, equipped with a single filament holder, the MUCIS-1990 has two filament holders. That required the installation of additional cables and connections for high electric currents (up to 200 A) every time switching between MUCIS-1990 and another gaseous source. This procedure costed additional time and efforts. Furthermore, there were notable thermal losses in the connection points, which led to heightened power consumption. To improve this situation, a special high current splitter has been constructed and installed on the Terminal North, together with the implementation of enhanced electrical connections for all gaseous filament driven ion sources (Figure 70). The new solution allowed us to reduce the thermal losses in the connection points (the maximum temperature in the connection point at full power filament operation measured using a thermo-scanner was reduced from 150°C to 70°C), as well as provided a possibility for faster and more convenient filament exchange and switching between various ion sources.

New ion species for operation

A big part of the ion sources research program in 2022 was dedicated to develop new ion species for the experiments. This year, investigations were focused on the isotopes Sc-45, Mo-94, Mo-100 and Sn-112 in order to fulfil the requirements of the APPA and NUSTAR research programs at GSI. All elements were tested with a vacuum arc ion source VARIS [2], which is regularly used for the production of high current metal ion beams at GSI. The tests have been performed on the Terminal North and the HSI-LEBT during the shutdown in October-November 2022. The results of the tests are summarized in this table:

Element	Scandium	Molybdenum		Tin
Isotope mass:	45 (mono-isotopic)	94 (9.2% in nat.)	100 (9.7% in nat.)	112 (1% in nat.)
Clear separation in LEBT from natural composition:	YES	YES	YES	NO
Ion charge state:	2+	2+, 3+	2+, 3+	2+
Repetition rate/pulse length:	2 Hz / 0.6 ms	1 Hz / 0.4 ms	1 Hz / 0.4 ms	1 Hz / 0.5 ms
Operational stability:	excellent *	good *	good *	satisfactory *
Ion beam current in UH1:	7.5 mA	0.18 mA (3+)	0.6 mA (3+) 0.4 mA (2+)	(14 mA) **
Number of particles in a 100 µs pulse:	$2.3 \cdot 10^{12}$	$3.8 \cdot 10^{10}$	$1.3 \cdot 10^{11}$	($4.4 \cdot 10^{12}$) **
Operation lifetime of a single cathode:	> 20 hours	> 24 hours	> 24 hours	> 5 hours

* Operational stability is defined by pulse-to-pulse intensity fluctuations as following: excellent (<10%), good (<15%), satisfactory (<20%)
** Values expected for enriched material, if it is available on the market

Scandium beam has never been performed at GSI before. However, the first attempt was right away successful. The charge state distribution of ions in the plasma was as following: 2% of Sc^{+}, 88% of Sc^{2+} and 10% of Sc^{3+}. Thereby, the production efficiency was maximum for Sc^{2+} ions. The $^{45}Sc^{2+}$ ion beam has shown excellent operational stability with pulse-to-pulse intensity fluctuations of less than 10% for both 1 Hz and 2 Hz repetition rates. The optimum beam pulse length was 0.6 ms. 7.5 mA of $^{45}Sc^{2+}$ were achieved in the UH1-section of the LEBT, which corresponds to $2.3 \cdot 10^{12}$ particles in a 100 µs beam pulse. Since scandium is mono-isotopic, there is no need for isotope separation in the beamline. So the LEBT has been tuned for best transmission and maximum ion beam current in the UH1-section. It was observed that admixing of He into the ion source as an auxiliary gas allows to increase the intensity of the Sc^{2+} beam by up to 15% and also to improve the operational stability. The lifetime of a single Sc-cathode reached more than 20 hours.

In contrast to scandium, molybdenum was already performed at GSI from high current ion sources before [3]. A beam current of 5 emA was reached for a Mo^{3+} ion beam in UH1. However, this result was achieved for the natural mix of isotopes without separation in the beamline, pointing to working with enriched material. Molybdenum has seven stable isotopes in the natural composition and each of both desired isotopes compose less than 10% of the total mix (9.2% of Mo-94 and 9.7% of Mo-100). Taking into account that enriched material for both Mo-94 and Mo-100 isotopes is hardly available on the market and very expensive, it was necessary to test the possibility of clean separation of desired isotopes from the natural composition in the HSI-LEBT.

The tests with molybdenum have shown that using horizontal slits and fine tuning of the LEBT, it was possible to clearly separate both isotopes in front of the HSI-RFQ. The optimum operational performance has been achieved for the Mo^{3+} ion beam with a repetition rate of 1 Hz and a beam pulse length of 0.4 ms. Ion beam currents of 0.6 mA for $^{100}Mo^{3+}$ and 0.18 mA for $^{94}Mo^{3+}$ have been reached in UH1. That corresponds to $1.3 \cdot 10^{11}$ and $3.8 \cdot 10^{10}$ particles in a 100 µs beam pulse for Mo-100 and Mo-94, respectively. The Mo^{3+} beam showed stable operation with pulse-to-pulse intensity fluctuations below 15%. For Mo^{2+} ions it was possible to reach similar particle intensities as for Mo^{3+}, however, with slightly reduced operational stability. Using He as an auxiliary gas to molybdenum notably increased the production efficiency of Mo^{3+} ions as well as drastically improved pulse-to-pulse stability of the Mo^{3+} beam during the operation. Mo-cathodes from various production charges (melting and sintering) have been tested. No notable difference in operational performance was observed. The lifetime of a single Mo-cathode reached more than 24 hours.

Tin is a poly-isotopic element containing only 0.97% of Sn-112 in the natural composition. Due to a weak signal from Sn-112 and some boundary conditions, the isotope separation in the beamline was not succeeded during the test. Thus, the test results with tin could be pointing to working with enriched or partly-enriched material. Tin is a very soft and fusible metal. In order to avoid melting and mechanical deformation of the cathode during the operation in the VARIS, alloying material Sn-Cu (10% Wt.) has been used in cathodes. The optimum operational performance has been achieved for a Sn^{2+} ion beam with a repetition rate of 1 Hz and a beam pulse length of 0.5 ms. An ion beam current of 14 mA, corresponding to $4.4 \cdot 10^{12}$ particles in a 100 μs beam pulse, has been reached for Sn^{2+} in the UH1-section. The estimated lifetime of a single Sn-cathode is above 5 hours.

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9.17 Recent developments on early prediction system for metallic ion beams with ECRIS at GSI

Authors: Alexandr Andreev, Oksana Geithner, Wolfgang Geithner, Ralph Hollinger, Simon Kundrat, Ralf Lang, Fabio Maimone, Jan Mäder, A. Müller (Technische Hochschule Darmstadt), Patrick Tedit Patchakui

The CAPRICE ECR Ion Source (ECRIS), installed at the High Charge Injector (HLI) of GSI, allows to produce highly charged ion beams from gaseous and metallic elements. The method of thermal evaporation with resistively heated ovens is used to produce metallic ion beams. This allows to efficiently produce metallic ion beams with low material consumption, which is important for production of ion beams from rare or extremely rare isotopes, such as e.g. ^{48}Ca [1].

A continuous development for metallic ion beams produced with the CAPRICE ECRIS is mainly focused on improving ion beam stability and intensity [1]. The operation with chemical reactive elements is associated with deposition of material inside the plasma chamber and internal components of the ECRIS. Occasional plasma instabilities can cause material outbursts or deteriorations and thereby decrease the ion beam stability and intensity. Since the solid material has to be evaporated first, the subsequent ECRIS optimization takes longer time in comparison with the gaseous ions production. The ECRIS optimization is also hindered by evaporation of the above-mentioned deposited material. In order to detect the upcoming instabilities early and thereby avoid resulting long ECRIS optimization, a prediction system based on a machine learning approach is currently under development [2].

The information on the spectral content in the visible wavelength range, which is measured with an optical emission spectrometer, looking through the ECRIS extraction aperture, allows to analyze the internal plasma parameters. For example, during operation with the most requested element, ^{48}Ca, a time variations of spectral lines at 732 nm and 827 nm are strongly related with the amount of material inside the plasma chamber and the resistive oven temperature, respectively. This data, together with the information on the ion source parameters and settings adjusted during operation, describe the ECRIS condition. These ECRIS parameters are the oven and microwave power levels, the auxiliary gas flow, the currents of injection and extraction solenoids, the extraction and screening electrode voltages as well as the drain current of the extraction power supply and the beam current transformer readings.

The ion source settings recorded with a 5-minute interval by the data logging system during beam times in 2020 and 2021 were used for this practical research. In total, this data set corresponds to 43 days of ^{48}Ca^{10+} operation. The prediction of the possible ECRIS instabilities has been treated as a time series classification problem. The applied model is based on a convolutional neural network. It assigns data points to one of the two classes. The first class is called “normal” and corresponds to stable ECRIS operation. The second class, called “anomalous”, consists of data points where deviations from the regular ECRIS operation pattern occur due to either material outbursts or deteriorations. All the points of the input time series were marked as either normal or anomalous based on the ECRIS condition. The input time series are divided into 8 hours subsequences using a sliding window, which are then processed by the model. The output of the model is the probability of an anomalous state [3].

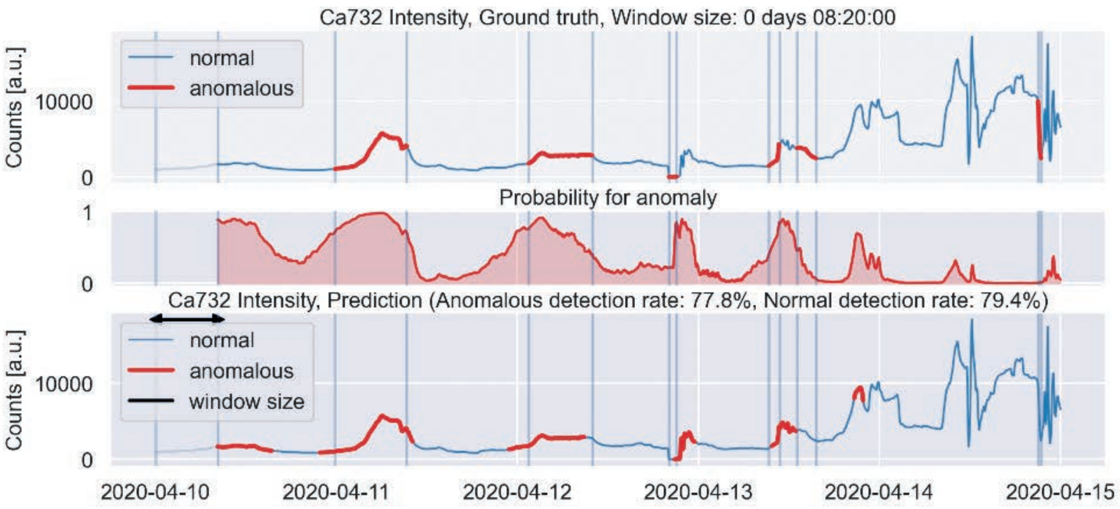

Figure 71. Example time series with measured spectral line at 732 nm (upper plot), probability of an anomalous state (middle plot) and model prediction (lower plot).

Figure 71 shows an example with a test data series from the beam time 2020. The uppermost plot shows the variation of the spectral line at 732 nm with time, where plasma instabilities are marked with red. The output of the model is shown on the middle plot and the anomalies detected by the model are shown on the bottom plot. The output of the model does not depend on the absolute magnitude change of the material evaporation rate, but mainly depends on time before the instability occurs. One can note that the algorithm performs quite well for detecting instable conditions, which take a long time to develop. On the other hand, the model ignores fast occurring instabilities. The sensitivity and specificity achieved by the algorithm on test time series are 0.75 and 0.8, respectively [2]. Provided that the developed system is further optimized to detect fast occurring instabilities, it is able to support the metallic ion beams operation with the ECRIS.

An open-source data visualization and monitoring software Grafana is another important tool, which has already supported the beam time operation in 2022. It was used to display time variations of the most important ECRIS parameters, which is particularly helpful for the ECRIS optimization. Grafana was also used to identify and mark anomalous periods for the machine-learning algorithm. In combination with the instability prediction system, it could be used to inform an operator if the anomaly probability threshold is exceeded.

References

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- [3] F. Maimone, A. Adonin, A. Andreev, et al.: Recent Developments in the Production of Metallic Ion Beams at GSI. Proc. of ECRIS2022, Bhat, Gandhinagar, Gujarat, India, 2022, unpublished

9.18 Production of ^{6}Li^{1+} and ^{58}Ni^{1+} for beam time operation with Penning ion sources

Authors: Rustam Berezov, Ralph Hollinger

The Penning Ionization Gauge (PIG) ion source provided different ion species as ^{56}Fe^{2+}, ^{40}Ar^{2+}, ^{209}Bi^{4+}, ^{197}Au$^{6+/8+}$ and ^{136}Xe^{6+} for the user beam time 2022 with sufficient performance and in stable operation. Only a vacuum failure in the ion source chamber during the 197-Au run occurred, which could be solved in short time. The delivery of ^{58}Ni^{1+} for the HITRAP commissioning and the production of ^{6}Li^{1+} for the NUSTAR SFRS as well as the UNILAC-biophysics program with a duty cycle of 5 Hz at 1 ms have been the main achievements.

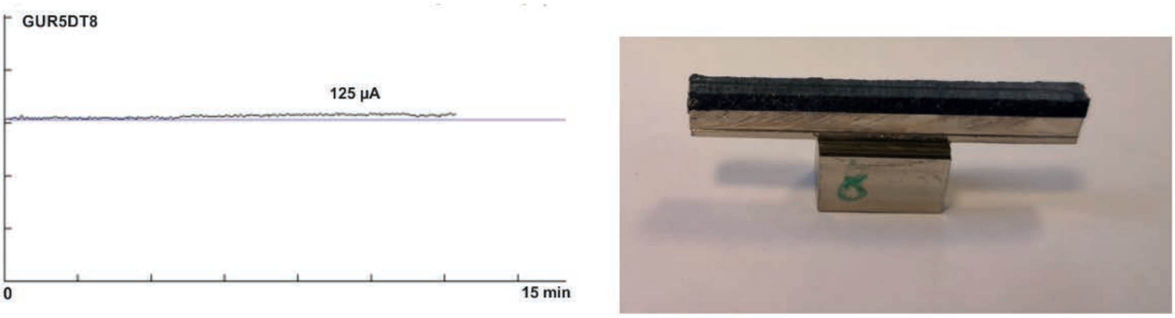

Figure 72. Left: Operation stability and intensity of ^{6}Li^{1+} over 15 min at beam transformator GUR5DT8; right: Lithium-electrode.

The first test with natural Lithium having two stable isotopes, 6-Li (7.59 %) and 7-Li (92.41 %) has been performed end of 2020. Several cathodes were tested composed of pure Lithium and a different mixture of composite materials. This test has shown excellent beam performance in terms of intensity and pulse to pulse stability. It was decided to use cathodes made of composite Li-Al (5-30 wt%), namely aluminum with enriched 6-Li to achieve the higher intensities required for the user experiments. These cathodes were manufactured by HMW Hauner GmbH. A 6-Li cathode ready for installation in the PIG ion source is shown in Figure 72 right. A total operation time of 10 days during beam time has been obtained using three different PIG sources, which leads to a service life time of 70-80 hours for each ion source. The maximum intensity of 0.1 emA has been achieved, corresponding to $9.8\cdot10^{10}$ particles in front of the High Current Injector (HSI)-RFQ and $2.6\cdot10^{9}$ particles in the transport section GTK7DT3 to the SIS18, respectivel. The ^{6}Li^{1+}-beam performance was highly stable for all cathodes during the beam time. The current measured in section GUR5DT8 is depicted in Figure 72 left.

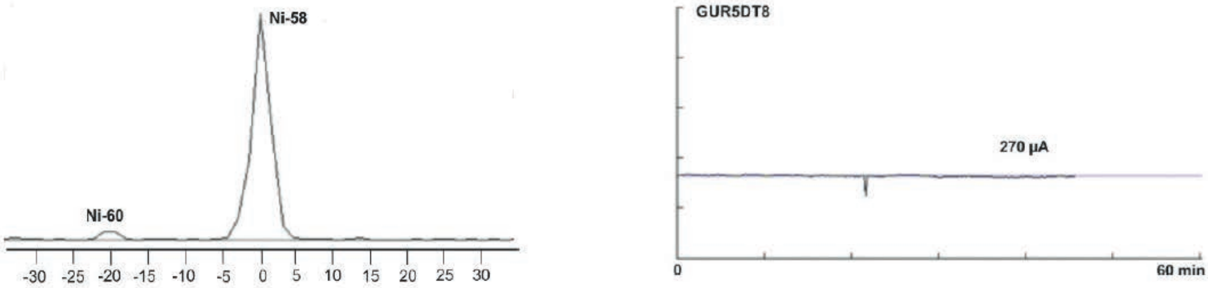

Figure 73. Left: 58-Ni and 60-Ni at profile grid GUR5DG7; right: Operation stability and beam intensity of ^{58}Ni^{1+} over 60 min measured in section GUR5.

Another PIG operation highlight is related to the production of ^{58}Ni^{1+}beam. Two closed stable isotopes 58-Ni (68 %) and 60-Ni (26 %) were separated in the low energy beam transport section. Figure 73 (left) shows the separation of two isotopes, which has been measured at the profile grid behind the bending magnet. The total operation time of 12 days has been obtained with four different PIG ion sources only, resulting in a similar life time of 70-80 hours for each source. The maximum intensity of 0.27 emA has been achieved, corresponding to $3.5\cdot10^{11}$ particles in front of the HSI-RFQ and $5.8\cdot10^{8}$ particles in the transfer line to SIS18, respectively. The beam performance of ^{58}Ni^{1+} in terms of operation stability and high intensity is shown at Figure 73 (right). Several sparks in the HV branch, leading to short beam interruptions, have been observed. This was justified by the fact that for the ^{58}Ni^{1+} operation a nearly maximum field current of the source magnet (230 A) and maximum high voltage of 111 kV was necessarily applied. An operating program has been carried out by the accelerator control system department in order to switch on the HV-power supply automatically in case of sparking.

It is planned to investigate the sparking behavior in the HV-circuit in Terminal South during the shut-down in 2022/23. Besides it is scheduled to test 54-Cr ion source operation applying enriched material during the engineering run. The first test with natural Chromium beam comprising 2.3 % of the isotope 54-Cr has shown an adequate performance at high duty cycle (25%). This test has been carried out by measuring the beam intensity behind switching magnet directly in front of the quadrupole quartet. Further tests at the gas stripper section are mandatory in order to improve the Chromium beam performance.

Further investigations are ongoing at the PIG test bench and at the Terminal South to obtain most stable operation at 50 Hz / 5 ms in particular for 50-Ti operation. New ceramic insulators must be installed in all sputter ion sources. High duty-cycle tests of the isolator showed promising results compared to the previous Polyoxymethylen (POM) isolators.

The authors would like to acknowledge the beam operating crew for their support during PIG ion source operation.

9.19 Status report/HELIAC-project

Authors: Maksym Miski-Oglu, Winfried Barth, Markus Basten, Christoph Burandt, Florian Dziuba, Viktor Gettmann, Szymon Kowina, Thorsten Kürzeder, Simon Lauber, Julian List, Stepan Yaramyshev

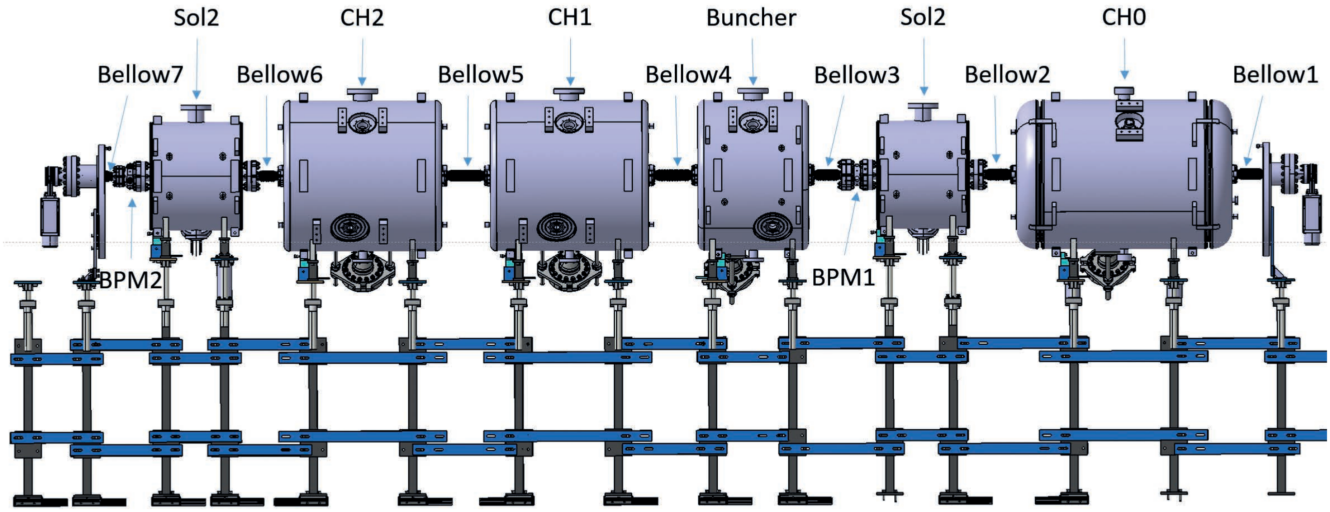

Figure 74. 3d Model of the CM1-accelerating string at clean room (CH-cavities CH 0-2; Rebuncher, Beam Position Monitors BPM1 and 2, bellow connection 1-7).

In 2020, the design of the cryogenic module prototype (Advanced Demonstrator) has been finished. This standard module is going to be equipped with three superconducting (sc) Cross bar H-mode (CH) acceleration cavities CH0-CH2 and a sc rebuncher cavity, as well as two sc solenoids. For stable 4K operation of the entire cw-Linac HElmholtz LInear ACcelerator (HELIAC) a cryo plant with 240W total cooling power@4K is required. The cryo plant of the GSI-Series Test Facility (STF) has a cooling capacity of 700W and is already in operation for testing of sc SIS100 dipole magnets. After magnet testing is finished, the cryo plant is dedicated to supplying the HELIAC and the testing area in the “GSI-Stripperhalle” SH1/SH4. The helium supply infrastructure for the testing area is still in operation (since 2020). In preparation for further beam test activities, the beamline, which connects the High Charge State Injector (HLI) with the testing area, was installed. The beamline comprises a pair of phase probes for Time Of Flight (TOF) measurement of the incoming beam energy, quadrupole lenses, and a 4-gap RF-buncher cavity. In preparation for a beam test in June 2021 the cryostat equipped with two sc solenoids and CH-cavity-dummies has been delivered and installed into the radiation protection shelter. The beam diagnostics bench behind the cryostat is equipped with phase probe pairs, a slit-grid emittance meter, and a bunch shape monitor (Feshenko monitor) for longitudinal beam profile measurements. This setup allows a complete 6d characterization of the ion beam. Altogether, the infrastructure and the individual accelerator components are ready for the beam test of the cryogenic module in 4th quarter of 2023, which is a major milestone for the entire HELIAC-project.

The assembly of superconducting components requires a cleanroom environment in order to avoid contamination with dust particulates. The laboratory at Helmholtz Institute Mainz (HIM) comprises amongst other things a cleanroom (CR), which serves as an infrastructure installation for the SRF projects at GSI in Darmstadt and Johannes-Gutenberg University (JGU) in Mainz. Besides different locks, the clean room is mainly divided into two parts: a 42m^2 ISO-class 6 area (CR1) for cleaning and preparation, and a 43m^2 ISO-class 4 (CR2) area, designated for drying and assembly. The clean room features a heavy-duty aluminum double floor, and a rail system through its different zones in order to roll out a complete cold string. Figure 74 shows the 3d model of the cold string for CM1 to be assembled in a clean room. The main components of the cold string i.e. the cavities, solenoids, and vacuum valve subassembly are supported with trolley stands and should be successively assembled together. The main components, bellows, and fasteners are cleaned just in time in preparation for the next step, intrinsically the stockpiling of the cleaned components leads to contaminations with particulates.

Highlights 2022

Figure 75. Integration of the rf-power coupler into a superconducting cavity (left); interconnection of the sc solenoid and the CH2 cavity (right).

The photograph on the of Figure 77 shows the integration of the rf-power coupler into the CH2 cavity - on the left side the interconnection of CH2 cavity and solenoid S2 applying a vacuum below is depicted.

Outlook for 2023

The RF-commissioning of the cavities mounted as a string inside the “Advanced Demonstrator” cryogenic module setup in the test area at GSI is scheduled for Q2 2023. Beam commissioning of the cryomodule is planned for November 2023.

9.20 Beam commissioning of p-Linac diagnostics

Authors: Thomas Sieber, Peter Forck, Kajetan Fuchsberger, Wolfgang Kaufmann, Christoph Krueger, Kevin Lang, Serban Udrea

Key diagnostics components in the FAIR proton Linac (p-Linac) are the capacitive Beam Position Monitor pickups, for measurement of beam position, relative intensity, and beam energy (via time-of-flight method) as well as the Secondary Electron Emission (SEM)-grids for detection of beam position, profile and (in combination with slits) transverse beam emittance.

Concerning the SEM grid design, we expect a 1σ beam radius of 1.5 mm at the best possible beam quality in p-Linac, therefore the wire pitch cannot be larger than 0.5 mm to obtain reasonable profiles. To compensate for the thermal expansion of the wires, a stretching mechanism is required - even if the grids are operated in a grid protection mode at a reduced duty cycle. Gold plating on the tungsten wires has to be considered carefully because of possible melting and agglutination during irradiation.

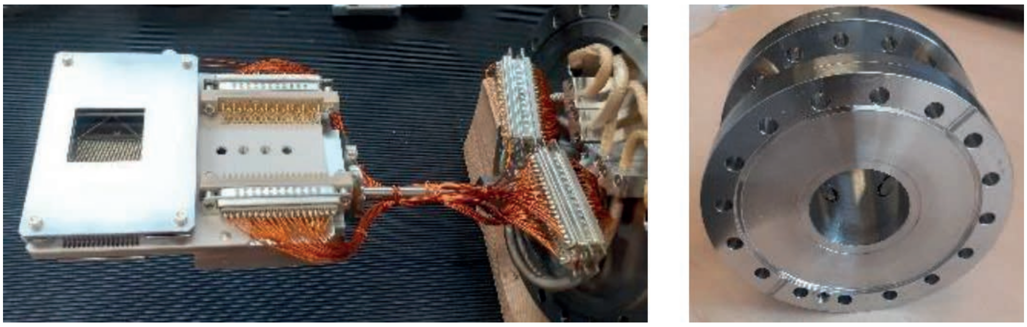

Figure 76. y-direction SEM grid (y-harp) by PROACTIVE (left) and 'Beamline' button BPM by NTG (right).

The BPM system of p-Linac comprises button BPMs in combination with a custom-made preamplifier including narrowband amplification (single button signals) for the frequency domain LIBERA (Single Pass H, LSPH) electronics and wideband amplification (sum signal) for an oscilloscope-based time of flight (TOF) measurement.

The components as shown in Figure 76 were developed and built together with the companies PROACTIVE (SEM grids) and NTG (button BPMs). Beam tests were performed in the UNILAC X2 beamline in February and June '22. In the first campaign, a low-intensity proton beam was used, and a second experimental campaign was performed with a high-intensity Ar beam to check the wire stretching system of the grid, the upper limit of acceptable energy deposition, and the actual heat load in comparison to simulations. The beamtime started with gold-plated wires, later we switched to a harp with regular tungsten wires - at this point we used an Ar^{10+} beam at 8.6 MeV/u, intensities 20 µA to 1.5 mA, pulse length 40 µs to 200 µs, repetition rate 1 Hz.

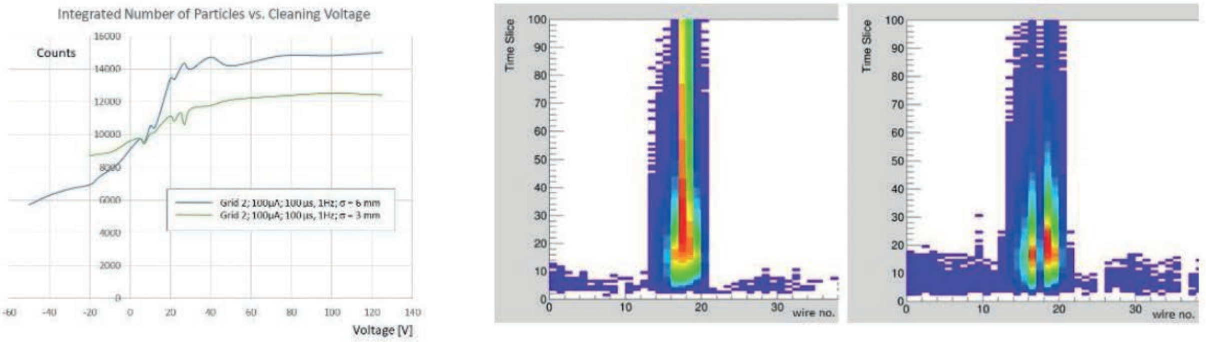

Figure 77. At the left: Number of particles, as a function of cleaning voltage. Sigma values indicate the beam size assuming Gaussian distribution in the calculations. Middle and right: Development of the beam profile during a 70 µs macro pulse before (middle) and after (right) destruction of one wire. A time slice corresponds to 5 µs.

We first checked the effect of the voltage on the diamond-shaped cleaning electrode while varying beam size and intensity. Figure 77 (left) shows the voltage dependence of the integrated number of particles for two different spot sizes. If the maximum current on the grid wires (maximum total counts) is taken as a criterion for optimum voltage, there is obviously not much effect from the cleaning electrode above ~40 V, which significantly reduces the effort for electrical connections. A comparison of the two curves in Figure 76 shows that the number of counts is reduced most likely due to geometrical aspects at the smaller number of wires, while an effect on the slope of the curves cannot be observed (at given accuracy), which is a strong hint for a homogeneous field distribution as a result of our electrode geometry optimization.

At inspection the gold-plated grid showed no damage, even after heating to (calculated) >2500 K. From this we concluded, that the wire temperature might have been overestimated in our calculations (pyTT code, [1]). Beam parameters (such as beam size, beam intensity, pulse length, etc.) and material properties (such as emissivity) are crucial for accurate thermal modeling. Big uncertainties on beam spot size and the emissivity of the material yielded too large uncertainties in the predicted temperatures. In an ideal case, temperature calibration measurements should be performed, which could not be done for several reasons. Thus, the harp was irradiated in the regular UNILAC grid protection mode, which at a spot size of σ = 3 mm an intensity of 500 μA and a duration of 40 μs corresponds to a (calculated) temperature of ~2800 K. Starting from this point, the intensity and the pulse length were stepwise increased to 1.4 mA, 40 μs, which lead after a final step to 70 μs to the destruction of some wires (T_{calc} = ~4200 K). The reasons for the strong increase of the current in Figure 77 (right), besides the position of the broken wires, and its duration is to be discussed. Several aspects contribute to the dynamic development of the profile, like the time constant of the electronics and intensity variation during a macro pulse. To what extent thermionic emission plays a role has to be investigated. Analysis of the results and adjustment of our theoretical model is ongoing.

The proton beamtime at UNILAC in February also had the purpose to test the whole BPM chain for the first time: button BPMs, preamplifier, LIBERA electronics as well as the FESA control software. We used an 8.6 MeV proton beam with an intensity of 100 - 300 μA and two BPMs, as shown in Figure 77 (right), installed 325.5 mm apart to allow for TOF measurements. The bunches arrived at 36 MHz, we used a 50 μs window within the 200 μs macro pulse (1 Hz operation). During the tests, the full functionality of the system could be demonstrated. Position and TOF measurements with the LSPH/FESA were verified by parallel oscilloscope measurements. The various algorithms in FESA, for the position [2] and phase calculation, showed excellent agreement. By variation of the beam current, it was shown that the FESA class switches dynamic range as required. In total, the system is - except for minor optimization steps and a missing GUI - considered ready for operation. An interesting side aspect of the tests was that dispersive effects in the beam transport at UNILAC could be identified by phase (and also position) shift between the horizontal buttons. Figure 78 shows data read out directly from the LSPH. The x-position measurement shown in the middle nicely illustrates how the beam position changes during the macro pulse, induced by the bending dipoles (and UNILAC energy deviation). The phase measurement shows accordingly how the left side of the beam (orange) precedes the right side (red).

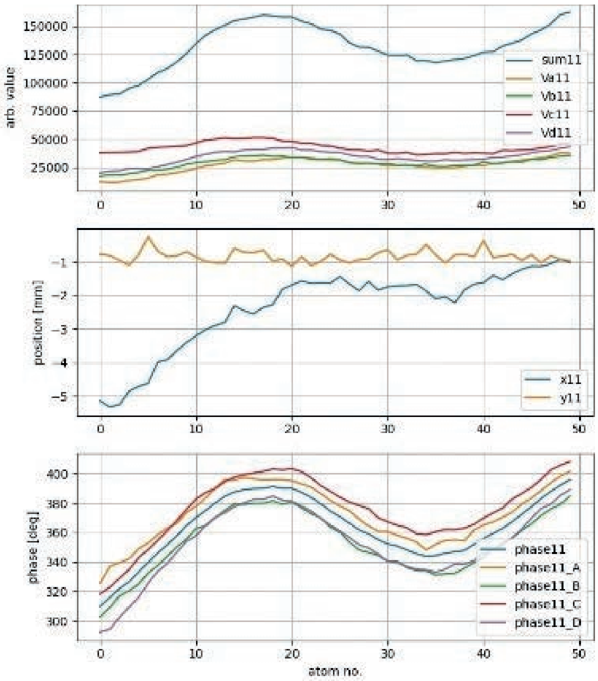

Figure 78. Position and phase measurement from LSPH; upper: button signals and sum signal over 50 μs; middle: position values; lower: corresponding phase; atom no. = channel number, channel width: 1μs.

References

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9.21 Advanced signal generation for tune measurement and slow extraction

Authors: Philipp Niedermayer, Rahul Singh, Oleksandr Chorniy

A signal generator for transverse excitation of stored particle beams was developed and commissioned at SIS18 and ESR. The device is used to control the coherence and amplitude of transverse oscillations by excitation in the vicinity of betatron sidebands. Applications include the measurement of beam parameters like tune and chromaticity, as well as knock out driven slow extraction.

For the realization of the signal generation, a novel approach using a software-defined radio (SDR) system and the open-source GNU Radio framework is taken. The SDR transceiver technology implements digital signal processing in software, thus allowing for a highly flexible yet cost efficient setup for creation of customizable and tunable signals from DC to 10 MHz. GNU Radio is used for the graphical design of signal processing flow graphs and control of signal parameters.

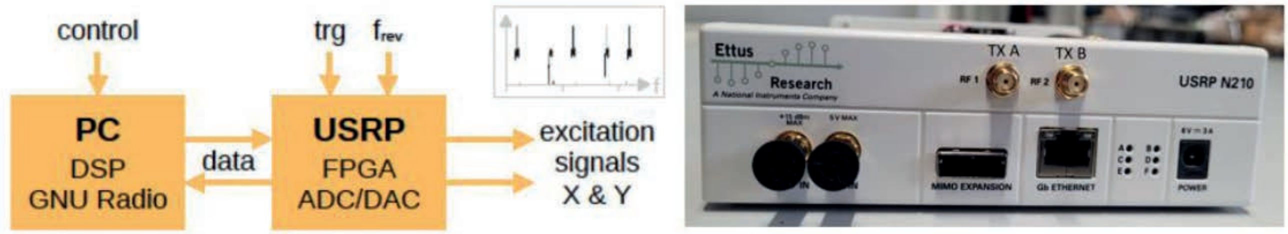
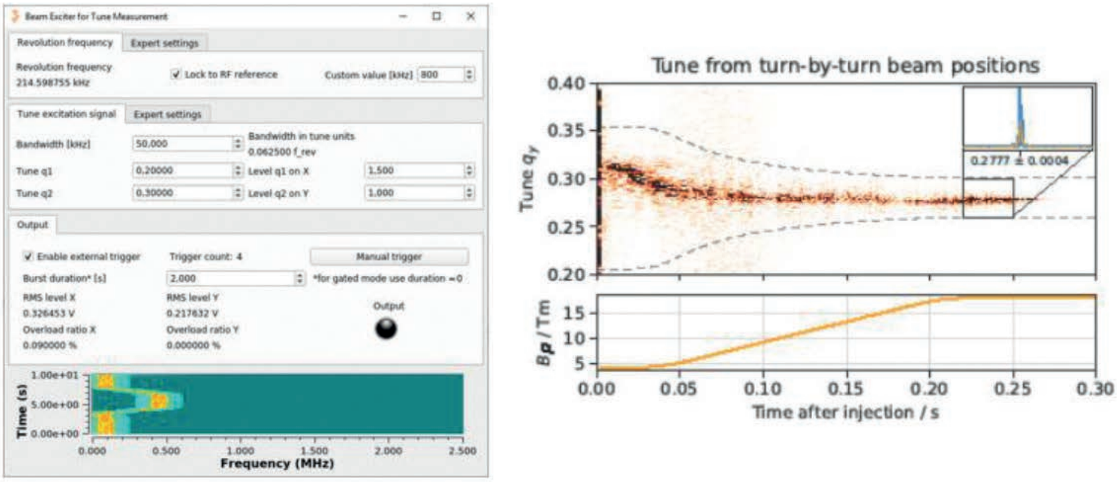


Figure 79. Signal generation scheme (left) and universal software radio peripheral hardware (right)

Figure 79 left depicts the working principle of the signal generator: As RF frontend, a universal software radio peripheral (USRP, Figure 79 right) equipped with ADCs and DACs is used. It digitizes input signals such as the revolution frequency reference signal (frev) and the trigger (trg). The data is streamed via Gigabit Ethernet to an industrial PC, where GNU Radio performs the digital signal processing (DSP). The generated signals are finally streamed back to the USRP and delivered at the two RF output ports.


Beam Exciter for Tune Measurement

Revolution frequency | Expert settings

Revolution frequency
214.598755 kHz
☑ Lock to RF reference
Custom value [kHz]: 800

Tune excitation signal | Expert settings

Bandwidth [kHz]: 50.000
Bandwidth in tune units
0.062500 f_rev
Tune q1: 0.20000
Level q1 on X: 1.500
Tune q2: 0.30000
Level q2 on Y: 1.000

Output

☑ Enable external trigger
Trigger count: 4
Burst duration* [s]: 2.000
*for gated mode use duration =0
RMS level X
0.326453 V
RMS level Y
0.217632 V
Overload ratio X
0.090000 %
Overload ratio Y
0.000000 %

Figure 80. GNU Radio user interface for control of signal parameters (left) and tune measurement with the new excitation system (right)

For tune measurements, two bandlimited excitation signals are generated for the horizontal and vertical plane at the respective betatron sidebands of the revolution frequency. The produced RF signals are amplified and applied to the beam by means of transverse electromagnetic fields produced in a strip-line kicker. This excitation is used to increase the coherence of betatron oscillations, such that they can be measured with the beam position monitoring system. A Fourier analysis then yields the eigenfrequencies of the transverse motion as shown in Figure 80 right. The system has proven to be capable of exciting beams with the highest rigidity and throughout the acceleration ramp of a standard SIS18 cycle [1].

Outlook for 2023

The developed signal generator will go into routine-operation at ESR. A newer hardware with extended capabilities will be taken into operation and is planned to be used for studies toward automatic optimization of excitation signals.

References

- [1] Niedermayer, P. ; Singh, R.: Novel Beam Excitation System Based on Software-Defined Radio. In: Proceedings of the 11th International Beam Instrumentation Conference, IBIC2022, Kraków, Poland, JACoW Publishing, Geneva, Switzerland (2022), DOI:10.18429/JACOW-IBIC2022-MOP36

9.22 Fast, large-area, radiation-hard scintillation detector

Authors: Maxim Saifulin, Plamen Boutachkov

Ion beams from protons up to uranium with energies from hundreds of MeV/u to tens of GeV/u have to be characterized with the scintillation counting detectors. The detectors utilize the interaction of the ion beam with the scintillator which generates photons. A photomultiplier tube converts the light into an electrical signal. The detector produces one pulse for each detected ion, and these pulses are discriminated versus the baseline noise and counted.

A ZnO(In) scintillation detector with an active area of 45x45 mm^2 was developed and tested with 300 MeV/u heavy-ion beams from argon to uranium. The light pulse induced via ionoluminescence has a full width at half maximum below one nanosecond, which resolves any pile-up limitations for the current micro-spill structure measurements. The radiation hardness of ZnO is at least two orders of magnitude higher compared to plastic scintillators. Furthermore, the material can be annealed, restoring the luminescence properties of the material. This type of detector will be used for intensity and micro-spill structure measurements at the GSI/FAIR facility.

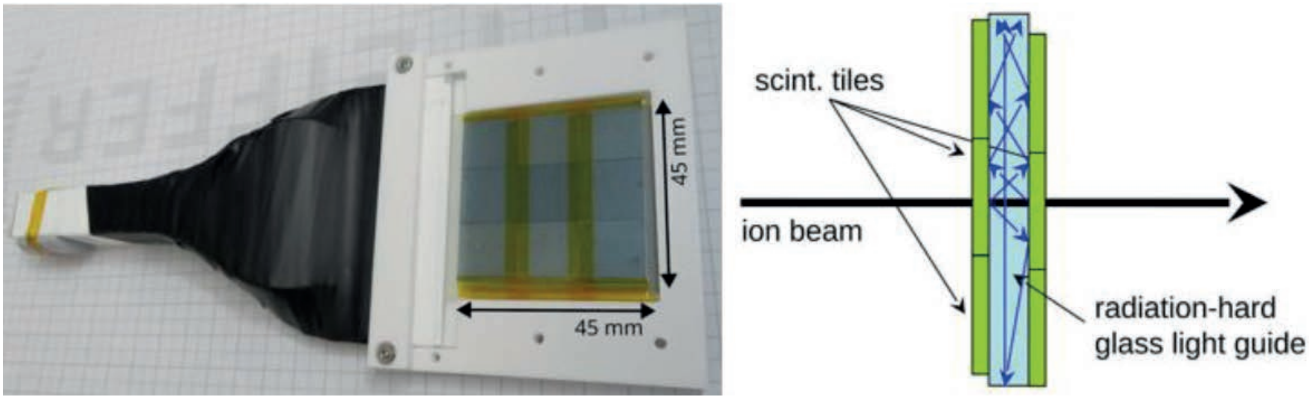


Figure 81. Left: Photographs of the ZnO-based multi-tile scintillator detector. The tiles are placed on the radiation-hard glass. The glass is glued to an acrylic light guide, covered in black tape in the photograph. The acrylic light guide is further attached to a photomultiplier (not shown in the photo). Right: A conceptual drawing of the multi-tile detector.

In a series of measurements, we investigated the response of ZnO(In) to heavy ions. References 1 and 2 summarize the results of these measurements. This research and development was performed within the ERA.Net RUS Plus Project. A large number of samples with ionoluminescence variation of the order of 30% were manufactured. In general, the light output of ZnO(In) ceramics obtained by the optimized manufacturing process is two times lower compared to the light output of the BC400 plastic scintillator. These samples were used to build the multi-tile detector shown in Figure 81 (left).

The production of the ceramic samples described in these studies is optimized for round samples with a diameter of the order of 25 mm. Square tiles with the size of 15×15 mm^2 were cut from the round samples. A detector prototype with an active area of 45×45 mm^2 was constructed from 18 tiles. Two layers of 3×3 tiles each were placed on each side of radiation-hard light guide. The interfaces between the front and back tiles were shifted. Thus, if a particle passed between two front tiles, it was guaranteed to interact with a tile on the back of the detector. A conceptual drawing of the tile layout is shown in Figure 81 (right).

The detector counting efficiency was validated relative to a 75×80 mm^2 BC400 plastic scintillation detector. All particles that passed the active area of the ZnO(In) detector generated a clean easy-to-discriminate signal. Hence, the prototype detector can be used in the high-energy transport lines of GSI/FAIR.

Outlook for 2023-2024

The developed prototype detector can be put into operation, allowing for higher counting rates and higher radiation resistance.

Reference

- [1] Boutachkov, P. ; Gorokhova, E. ; Rodnyi, P. ; et al.: Novel Fast Radiation-Hard Scintillation Detectors for Ion Beam Diagnostics. In: Proceedings of the 11th International Beam Instrumentation Conference, IBIC2022, Kraków, Poland Geneva, Switzerland : JACoW Publishing (2022), DOI:10.18429/JACOW-IBIC2022-WE3I1
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9.23 FAIR commissioning – status of preparation

Authors: Stephan Reimann, Sonja Schumann

In 2022, the work of the FAIR Commissioning Project Group, which was initiated to prepare a new FAIR subproject dedicated to the commissioning phase, was continued. Mainly, the commissioning planning and its integration with the commissioning of the technical building infrastructure and the accelerator control system was further advanced. In addition, a general procedural instruction for the commissioning phase and risk management were set up.

Planning status

A dedicated commissioning schedule was set up for the FAIR subprojects relevant to the intermediate objective scenarios. In all cases, the detailed planning was carried out down to the section level and to a large extent already down to the system level. The commissioning planning was linked to the preceding phases of the installation and mapped in the FAIR Level 1 plan. In this way, the FAIR project is now able to present a continuous schedule up to the completion of the beam commissioning for the relevant scenarios, which is also synchronized with the GSI integrated campus schedule and therefore includes beamtime phases for the FAIR Phase-0 physics runs. This planning is now to be refined on an ongoing basis using the LCM (lean commissioning management) workshops together with the work package leaders and the concerned technical groups. In this process, the personnel requirements are also to be assessed in detail.

LCM commissioning workshops

In dedicated workshops, the step-by-step commissioning process for each system type is currently being discussed in detail and formally written down. The dependencies and boundary conditions for these work steps are also collected so that they can be clearly represented, linked, and tracked in the project planning. During the workshops, the necessary personnel resources are assessed and an estimate of the duration of the commissioning steps is made. In the end, a set of documents with the required commissioning activities is to be created for each system type. In the past year, initial workshops have already been held for the following systems:

- beam instrumentation für HEBT,
- normal conduction magnets & power supplies,
- HEBT vacuum systems,
- HEBT diffusors,
- SFRS superconducting magnets & power supplies.

Quality assurance: general procedural instruction & risk assessment

For commissioning, a general process instruction was created together with the subproject leaders. The document describes the handling of components and systems for the commissioning process from M102 (milestone: assembly in tunnel finished = mechanical completion) to the completion of the beam commissioning with a pilot beam. The commissioning of a scenario ends when the Project Completion Parameters (PCP) can be reached stably at the respective beam target and the basic functions of the initial detector setup have been tested successfully. The document describes the prerequisites, the responsible roles, and the essential process steps. To be able to perform and repeat the commissioning checks automatically as far as possible, we have started to implement sequencer test procedures for frequently occurring device types such as power supplies for beamline magnets and pneumatic drives. A risk register was drawn up in parallel. The main risks for commissioning are:

- the outstanding funding of the commissioning phase,
- the availability of personnel resources,
- Synchronization and timely provision of the necessary technical building equipment,
- Serious damage to the injector chain due to aging or maintenance backlog.

All risks are addressed and regularly analyzed as part of the risk assessment process and attempts are made to mitigate or eliminate them.

10. Research & developments for the FAIR project

Head: Jörg Blaurock, FAIR & GSI
Author: Emmanuel Rosi, Mandy Raponi FAIR & GSI

Executive Summary

Figure 82. View on FAIR construction Site in CBM Cave December 2022.

In 2022, the FAIR project has made good progress in all areas but has also faced different challenges. Because of the corona pandemic and the associated economic effects such as higher inflation and bottlenecks in the global supply chain, the FAIR project mangement has announced additional costs for the completion of the project. An external audit initiated by the BMBF has confirmed this cost forecast increase and the detailed figures have been presented in an extraordinary FAIR Council meeting in March 2022. Subsequently, the Council has initiated a further scientific review aiming at defining a new staging of the FAIR project execution. The recommendations of the "First Science and Staging Review of the FAIR Project" have been presented to the Council in October 2022. Based on the recommendations the Council is to decide the way forward in March 2023 and allocate the corresponding budget enabling the continuation of the project.

Following the start of the war in Ukraine and the consequences of the European sanctions against Russia, the FAIR Council has stopped in September 2022 all the on-going project-related collaborations with Russian institutes. FAIR has elaborated a back-up plan to replace the missing Russian components which demonstrated that all components can be provided from the European market.

The civil works on the construction site have progressed well during 2022. Further buildings in the construction area North have been completed and handed over to the contractors for installation of the technical building infrastructure. This major milestone has been reached as planned when the Technical Building Installation (TBI) companies have started their work on-site in March 2022. Since then, TBI works progressed extremely well in the SIS100 tunnel and the Cryo-compressor building.

Another major milestone has been reached with start of installation of Cryo 2 Plant by company Linde (Switzerland) and the SIS100 cryogenic distribution system by company Demaco (Netherlands) in July. In November, the monumental Cryo 2 "Cold Box" (85 tons) has reached the FAIR construction site and was placed in its final position in the dedicated building. The series integration of 110 SIS100 dipole chambers into dipole modules could be completed successfully in Q2/ 2022. The time critical contract for the user cables was placed at the end of October 2022.

Figure 83. View on FAIR construction Site in CBM Cave December 2022.

The preparations for the FAIR experiments have made significant progress in the reporting period, e.g., an overall increase of 3.5% in construction has been achieved. In 2022, the main challenge is to find alternatives for Russian contributions.

Figure 84. Top left: Cryo 2 installed in Cryo building on site – Top right: Start of component installation on FAIR site – Bottom: Delivery of the Cryo2 Cold Box.

10.1 Research & developments of the division SIS100/SIS18 of the FAIR Project

Head: Dr. Peter Spiller

The integration process of 110 dipole chambers into the cryogenic dipole modules has been completed. Due to the Ukraine crisis, the collaboration in terms of the manufacturing of quadrupole units with JINR (Russia) has been suspended. In the mean time, negotiations have been continued, because JINR was recognized as an international research institute and does not fall under the sanctions imposed after the Russian invasion of Ukraine. To date no further units have been completed and shipped to GSI and measures have been initiated to compensate for these shortfalls. The number of units delivered so far, serve for completing the integration of 13 quadrupole modules at Bilfinger Noell (Germany). Consequently, the integration process has to be interrupted after assembly of these modules. Additionally, the module testing at the THOR facility in Salerno, will be suspended on short term. The whole reorganization of the assembly chain of quadrupole modules, creates a significant additional effort for the subproject and generates additional budget needs for investments and personnel. The replacement of the quadrupole unit manufacturing, expected to be conducted at JINR (Russia) by European industry is possible. However, the cold testing of the units needs to be performed at the GSI STF test facility. Due to resource limitations, GSI cannot conduct both, the cold tests of the units and the cold tests of the integrated modules, therefore, the continuation of the collaboration with INFN (Italy) is required. Cold testing of the integrated quadrupole modules has to be done in the test facility THOR in Salerno over the full prolonged subproject schedule. In order to prepare the production of the series of quadrupole units at an alternative manufacturer, the re-procurement of yoke steel and s.c wire, required for s.c. cables has been started by GSI. At the University Salerno, the preparation for the series testing of the quadrupole modules is well advanced. The set-up of the s.c. test facility as well as the cold commissioning has been completed successfully. The First-of-Series FOS quadrupole module, send to Salerno, has been integrated into the test facility and used to conduct the approved test program at room and cryogenic temperatures. The FOS testing did serve also for training the INFN colleagues. The series production of the thin-walled and actively LHe-cooled quadrupole chambers has been completed by the company RI (Germany). Thus the quadrupole chambers and all other parts to be combined in the quadrupole modules, such as cryo-ion catchers, cryogenic BPM system etc. are available and stored for the continuation of the integration process. The design of the main power converters has been completed by GE (General Electric) and was approved in the frame of the Conceptual Design Review (CDR) and Final Design Review (FDR) milestones. The procurement process for the extraction septum magnets 1 and 2, could be successfully passed and the contract for production is awarded. is in its final phase and contracting is expected on short term. The tendering process for the last device of the extraction system, the extraction septum 3 is presently in the negotiation phase. under preparation. With the contracting of these magnets, all devices of the extraction system will be in manufacturing process

After a slow start of activities, progress has also been achieved with mitigating the technical issues with the injection kicker system. With the present set-up of the FOS kicker system a first set of Factory Acceptance Test (FAT) measurements indicates acceptable performance. However, further investigations of the system are required. The delivery of parts and systems for the extraction kicker system is progressing. At company RI (Germany) a first Pulse Forming Network (PFN) system used for energy storage has been assembled and promising measurements have been conducted. The development of a forced air cooling system for the bunch compression cavities has been successfully completed at company AURION. The series integration of this system and preparation of the final power tests are presently conduced. The production of bypass lines by the company Kriosystem (Poland) was continued without incidents. To verify the quality and functionality of special technical details, such as the feed-through in the vacuum barrier, further bypass lines were cold tested at the GSI STF facility. Another invitation to tender for the production of the current lead boxes has been repeated and is presently published againcanceled by WUST (Poland) due to commercial issues. A concept and strategy to involve more potential bidders has been developed with the aim to enable a successful next procurement process also for the upcoming feed-boxes

In parallel to the procurement processes, the set-up of the string-test is under preparation. The string test consists of all components of one regular SIS100 lattice cell. Most important is the usage of the string test assembly not only for design confirmation and physical measurements, but also to develop the work instructions and QA processes and additionally to build up teams able to conduct the integration and assembly process of the overall cryomagnetic- and local cryogenic system in the tunnel.

This activity is developing very promising. Furthermore, the installation preparations have been further advanced. Sequences of installation and many details like final pre-integration works and design of tools for lifting and transportation advanced.

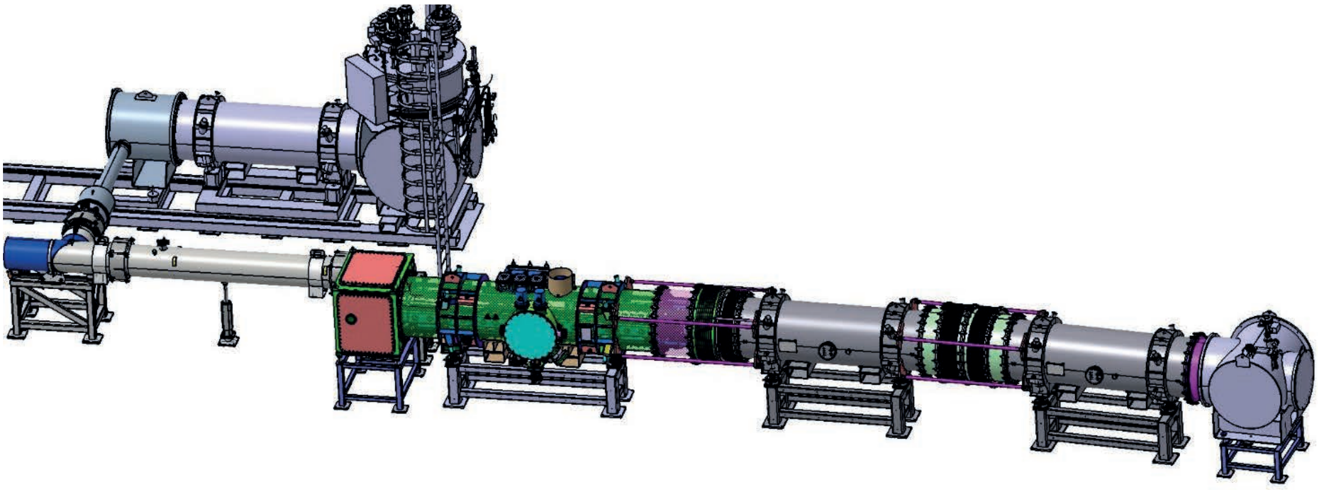

Figure 85. Planned SIS100 string test involving bypass line, quadrupole module, tow dipole modules and end box.

10.2 Research & developments of the division Super Fragment Separator of the FAIR Project

Head: Dr. Haik Simon

Being the most powerful in-flight separator in the world, the Super-FRS will provide clean and intense beams of unstable, short-lived nuclei to the scientific community, which are necessary to explore special properties of nuclides very far from the valley of stability. To achieve this goal, in the construction of the Super-FRS several technological challenges must be overcome: the realisation of remotely controlled components with reliable performances in a highly radioactive environment (the "target area"), the superconducting-magnet system allowing for large apertures, and the diagnostic systems with high-rate capability

Having concluded the R&D and design phase, 2022 was characterised mostly by the progress in production and testing of components. In addition, tenders of formerRussian components had to be prepared and started again.

The target area faces a particular technological challenge due to the special constraints imposed by the highly radioactive environment.

Among the ex-Russian components, the reorder of two radiation resistant dipoles for the target area is of extreme importance. Most critical here were the special mineral insulated cables, which only one manufacturer – nVent Thermal, Canada– could produce in the required lengths. The MIC cables were ordered; the purchase to replace the radiation resistant dipoles themselves was started and is ongoing.

Five radiation resistant multipoles will be placed in target area. In 2022, the conceptual design phase was concluded: almost all requirements were accomplished; even additional not specified wishes were fulfilled. The production started at Buckley Systems, New Zealand. The corresponding power converters were withdrawn from our Indian in-kind partner; they will be now purchased by tender, which recently started.

Based on the design for the target chamber by University of Groningen (KVI-CART) and for the beam catchers by CSIR-CMERI Durgapur, contracts with manufacturers were made. For the target chamber, which is a German in-kind contribution, Fantini Sud S.p.A in Italy was selected. For three beam-catcher chambers, directly ordered by FAIR GmbH, NTG Neue Technologien GmbH & Co. KG in Germany was chosen, while for the complete beam-catchers package, which is as Indian in-kind contribution, Trident Auto Components Priv Ltd. in India was selected.

With the production targets and the relevant beam diagnostics, the target chamber is of course essential for "Early Science" with Super-FRS. Similarly, the beam-catcher (BC) chambers are also a requirement for any beam operation in Super-FRS. For high intensity beams, the absorbers and built-in shielding must be mounted in these chambers. All chambers contain water cooled components and also provide water cooling for some outer chamber sides. The upper parts of the chambers are filled with steel shielding, while on the lower side beamline components are mounted on removable shielding plugs. Each chamber also has a shielded vacuum duct, through which this area of the separator will be pumped.

The design phase of shielding flask for the transport of activated targets was successfully concluded with the manufacturing company, BNG, Germany.

Figure 86. sc multiplets stored at the factory, ASG, La Spezia, Italy..

The series production of multiplets for the superconducting magnets is going at full speed at our provider ASG, Genoa (series production site is in La Spezia, Italy) Figure 86. Meanwhile all 7 Short Multiplets (SM) (plus one spare) have been produced and got their factory acceptance test (FAT). All SMs will be installed at the Pre-Separator of the Super-FRS within the early science objective. So far also 5 Long Multiplets (LM) out of 23 (plus one spare) have been manufactured and got their FAT. For Early Science, 13 out of the 23 LMs are required.

Figure 87. Super-FRS testing facility for sc magnets at CERN, Switzerland.

Cold tests and magnetic measurements of a site acceptance test, (SAT) of the magnets are done at the magnet test facility at CERN Figure 87. The facility consists of three test benches which are commissioned meanwhile. The SAT of the First-of-Series (FOS) SM and LM as well as for two series SMs were done [[A. Chiuchiolo et al., "Cold Test Results of the FAIR Super-FRS First-of-Series Multiplets and Dipole", in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 2796-2799. doi:10.18429/JACoW-IPAC2022-THPOTK013]] and in general SAT of series multiplets is ramping up. The performance of the CERN facility could eventually also be verified.

Also, two super conducting (sc) dipole units from our provider Elytt, Bilbao were delivered to CERN (FOS D2 = Pre-Separator; FOS D3 = Main-Separator). Unfortunately, both dipoles showed non-conformities (NC) during the SAT. While NC of FOS D2 could be repaired on site, we had to ship back FoS D3 for repair to Bilbao. The magnetic measurements of FOS D2 are meanwhile successfully finished and the dipole will to be prepared for shipping to GSI. The repair of FOS D3 is still ongoing and we expect to restart SAT at CERN in Q12/2023. The associated two vacuum chambers, originally assigned to Russian as in-kind contribution, were tendered and awarded to Omega Physics, Germany.

In 2022, we could also successfully ramp-up the personnel at the CERN test facility. We found a fifth GSI team member while CERN could hire a Test Facility Manager who coordinates together with the GSI team the daily business.

In 2022, we could welcome the first two superconducting multiplets on GSI campus. After the successful cold test (SAT) at the CERN Magnet Test Facility the First-of-Series (FS) Short Multiplet (SM) was shipped on March 11, 2022 to GSI and the FoS Long Multiplet (LM) arrived on Sept. 15, 2022. During the following pre-assembly phase some add-on parts still have to be mounted on the magnets before they are ready for the installation in the tunnel. This pre-assembly takes place at GSI "target hall" Figure 88, where a dedicated area was prepared for this work. The arrival of the first series multiplet at GSI is expected end of 2022. From 2023 on, it is expected that one magnet per 4 to 6 weeks will arrive at GSI. The pre-assembly is supported by colleagues from IFJ Cracow, Poland.

Figure 88. Running pre-assembly of FoS SM and FoS LM at GSI “target hall”.

A key component of the local cryogenic system, with which sc magnets will be cooled down to 4°K, is the branch box, that is the starting point for distributing helium to the Super-FRS experimental branches. The tender of the branch box, which was originally a Russian in-kind component, has started after a careful revision of the specifications.

All along the Super-FRS, vanguard detecting-system and radiation resistant electronics with very high rate capabilities of several MHz are being used. The detector and degrader systems are hosted in special vacuum chambers (called diagnostic chambers), located in each focal plane.

Figure 89. Diagnostic chamber at factory, Pfeiffer Vacuum Components & Solutions GmbH, Göttingen, Germany.

The purchasing of the first two beam-diagnostic chamber is now concluded. They were produced by Pfeiffer Vacuum Components & Solutions GmbH, Göttingen Figure 89. The chambers arrived on campus, were successfully tested (SAT approved), and are now available for use. They will serve as test benches for the different diagnostic elements (slits systems and different detectors) of the Super-FRS. The whole process from technical kick-off to delivery was completed in 8 months. The diagnostic chambers that will be installed in tunnel are ex-Russian components; their specifications were improved and are ready for starting the tender.

Figure 90. Slit systems at GSI storage.

In September 2022, all 17 slit systems produced by KVI Groningen (the Netherlands) were shipped to GSI Figure 90. The final acceptance tests (FAT/SAT) have been started at the GSI vacuum laboratory.

The design phase of the two Beam Stopper systems has been concluded by our provider Axilon AG (Germany). The corresponding Final Design Review (FDR) was approved in November 2022. The Beam Stoppers are mechanical safety devices which are integrated into the FAIR Personal Access System (PAS). In case of any (beam) failure they will safeguarding personnel working in the areas NE55 (High-Energy Cave) and NE57 (Low-Energy Cave) by intercepting and absorbing the beam by means of massive Densimet® Blocks. The beam stoppers are located at appropriate positions further upstream in the Super-FRS.

Diamond detectors are a part of the beam intensity monitoring systems. Two systems are required: one placed at the target station of the Super-FRS (FPF0) and one located at the entrance of the Main-Separator (FPF4). The system at FPF0 has to be integrated in one of the plug systems of the target chamber while the system at FPF4 is an independent drive insert. Both systems were originally Russian in-kind contributions. Due to schedule constraints, we started immediately an in-house development of these detectors in collaboration with DTL (GSI detector laboratory) in March 2022. Already in October 2022 the Conceptual Design Review (CDR) of the diamond detector system at FPF0 could be approved.

10.3 Research & developments for the proton linac and the pbar Target of the FAIR Project

Head: Dr. Klaus Knie

Proton-Linac (pLinac)/ pbar Target

Due to prioritisation within the FAIR project only minor progress have been achieved for the pLinac/pbar subproject.

In collaboration with the Billiger Noel Group the final design review for the pbar shielding flask with internal handling system has been completed.

A first-of-series tank of the pLinac CH cavities has been delivered to GSI. In order to have a maximum flexibility during RF commissioning, the stems are not yet welded but clamped. Low level RF tests have been started.

10.4 Research & developments for the Collector Ring of the FAIR Project

Head: Dr. Oleksiy Dolinskyy

Until the end of February 2022, BINP was responsible for the CR project and provided the main contribution to the development of the project in both human and financial resources. After the Russian invasion of the Ukraine, cooperation with BINP was stopped and all contracts were terminated. New options are being considered for the implementation of the CR project without the participation of Russia.

10.5 Research & developments for the High Energy Storage Ring of the FAIR Project

Head: Dr. Ralf Gebel

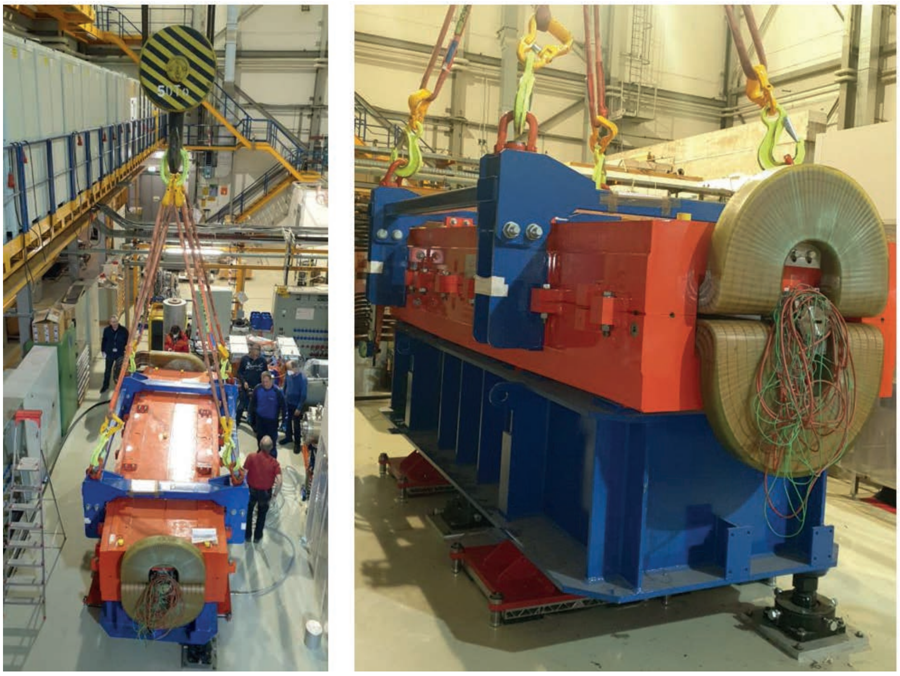

Figure 91. Air cushion tests on the dipole magnet on 20.12.2022 in the IKP test hall of For-schungszentrum Jülich. For safety reasons, the dipole was fastened to the indoor crane.

For the High Energy Storage Ring HESR the components are delivered to Jülich, where they are prepared for operation. The finalized elements are then transported to Weiterstadt where they are stored until installation.

Figure 92. Injection equipment Tank B ready for packing (left) and on the truck (right). Four magnets with pulsers and cables are in Weiterstadt now. The magnets are housed in 2 vacuum chambers pairwise.

For precise adjustment of the beam-bending dipole magnets at their final location an air cushion transport system will be used. This system has been successfully tested in December 2022 on one of the HESR dipoles; the magnet and its girder, which have a net weight of 35 tons, were moved on the air cushions. Subsequently the dipole was sent to the storage hall in Weiterstadt. As it has been the last remaining dipole in Jülich all 46 dipole magnets are ready for installation now. The injection dipole has been completed with final test measurements as well and is now ready for its delivery to Weiterstadt.

The second injection kicker tank with two kicker magnets has passed its acceptance tests and was delivered to Weiterstadt.

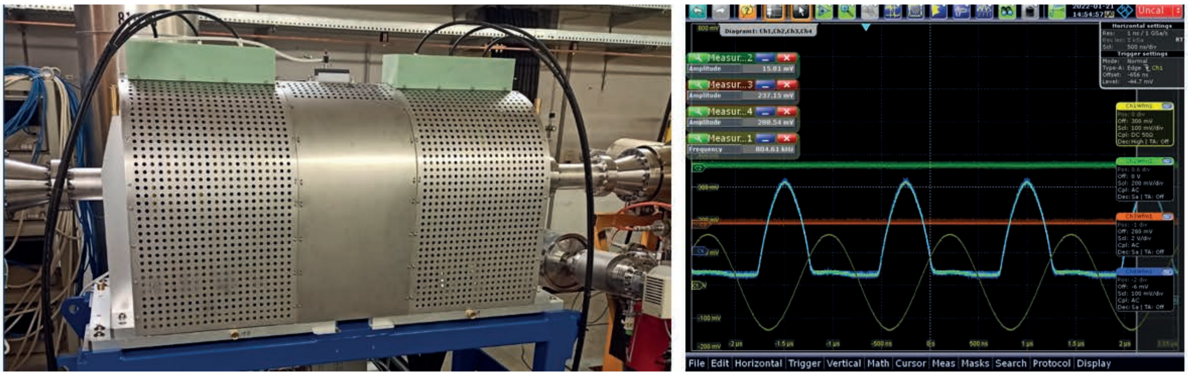

Figure 93. The HESR Cavity has been installed in the COSY tunnel (left). The recorded phase signal (right, light blue) shows bunching of the COSY beam in one of the early runs with the HESR cavity.

To test the accelerating radio frequency RF for the HESR at real operation conditions, one of the HESR cavities was installed in the Cooler Synchrotron COSY in late 2021. After some initial tests including the recording of calibration data, the cavity was used to accelerate the COSY beam during the whole beam time in 2022. As expected, it proved its stability and reliabilty,

10.6 Research & developments of the division Commons of the FAIR Project

Head: Stefan Menke
Authors: Dr. Marcus Schwickert, Dr. Andreas Reiter, Dr. Martin Eibach, Dr. Frank Hagenbuck, Dr. Carsten Mühle, Lukas Urban, Horst Welker, Dr. Christina Will, Dr. Stefan Zeller, Dr. Holger Kollmus, Mario Bevcic.

Dept.: Beam Diagnostics (BEA)

Authors: Dr. Marcus Schwickert and Dr. Andreas Reiter

In 2022, the BEA department focused on the completion of important development works, as many procurement processes significantly advanced or were completed.

To start with, the UNILAC machine experiments included final beam tests of the complete p-linac BPM measurement system, consisting of novel BPMs, specially designed 3 GHz pre-amplifiers, of Libera Single Pass H digitizers and of associated data acquisition software. Both the digitizers and the software are part of the Slovenian in-kind contribution for FAIR respectively provided by Instrumentation Technology and Cosylab. In addition, beam testing of the new high-intensity SEM profile grid was successfully completed in June 2022. A prototype had been developed in collaboration with the company Proactive (Spain) and colleagues from the CERN beam instrumentation department [BEA1]. Based on the positive results, the series production has been launched.

Then, tests of the novel Fast Faraday Cups commenced in 2022 to enable longitudinal bunch diagnostics as a routine operating tool for UNILAC in the near future [BEA2]. Works on the data acquisition for the Multi-Wire Proportional Chambers (MWPC) have well progressed and the electronic modules were also tested with beam. In the GSI detector laboratory, the production of MWPCs has continued, and a second detector emanated from the GSI in-kind contribution was tested at GSI with beam to back up first-of-series results.

Moreover, the production of mechanical components for the HEBT beam diagnostics took an important step forward during 2022. The thermal shield of the cryogenic current comparator for the HEBT section of FAIR was significantly improved, so the mechanical design of the cryogenic system is now being finalized for series production [BEA3]. As an important project milestone, the delivery and the SAT procedure of 58 diagnostic vacuum chambers by the Indian in-kind contributor Vacuum Techniques were completed in October 2022. The design work for the Ionization Profile Monitor vacuum chambers was completed in 2022 as well, and the tendering process has been launched. Furthermore, the Polish in-kind contributor Prevac delivered the full series of 49 SEM grid detectors for HEBT.

The Slovenian in-kind contribution, for this part, has almost been finalized. While the remaining work on FPGA and data acquisition software was completed in 2022, delivery of the remaining mechanical drives is scheduled for the first half of 2023. Meanwhile, the resistive coating of ceramic gaps for the GSI in-kind contribution on beam current transformers was successfully produced by Fraunhofer Institute IST (Germany) for 80% of the full series and will be most likely finalized in spring 2023.

Finally, in April 2022 the mechanical vacuum housings for a batch of 22 beam position monitors were ordered from the company TEES (Italy).

- [BEA1] T. Sieber et al. „Design and test of beam diagnostics equipment for the FAIR proton linac“, Proc. LINAC2022, TUPOJ006, Liverpool, UK, 2022.
- [BEA2] R. Singh et al. “Longitudinal beam diagnostics R&D at GSI UNILAC”, Proc. HIAT2022, TH2I2, Darmstadt, Germany, 2022.
- [BEA3] D. Haider et al. “The cryogenic current comparator at CRYRING@ESR”, Proc. IBIC2022, TUP31, Krakow, Poland, 2022.

Dept. High Energy Beam Transport (HEB)

Authors: Dr. Martin Eibach, Dr. Frank Hagenbuck, Dr. Carsten Mühle, Lukas Urban, Horst Welker, Dr. Christina Will, Dr. Stefan Zeller

Magnets

In the first weeks of 2022, three dipole magnets (dip10_0, dip13_0 and dip16_0), 10 quadrupole magnets (10x quad2) and 35 steerer magnets (16x s100 and 9x s18) arrived at GSI/FAIR from the Budker Institute of Nuclear Physics (BINP), Russia. Additional 18 magnets successfully passed their Factory Acceptance Tests there but could not be sent to GSI/FAIR due to the EU sanctions against Russia because of the war in Ukraine. At of today 51 of 51 magnets (batch 1, NIIEFA/Russia) and 121 of 303 magnets (batch2/3, including amendments, BINP/Russia) have arrived on site.

Assuming that no further magnets from Russia would reach Germany, different strategies for re-procurement of the 51% missing HEBT magnets were compiled and model-based cost estimates were made. Simultaneously the detailed specification for tendering the missing magnets for the “Early Science” scenario was finalized.

In the meanwhile, GSI had to assume manufacturer responsibilities for the magnets on site as communication with the Russian institutes was suspended. Therefore, GSI personnel completed the corrections on 45 different magnets that would have been the responsibility of the manufacturer. Furthermore, GSI started the major task to acquire all documents for receiving the CE certificate.

Power Converters

The power converters for HEBT quadrupole and steering magnets will be mainly built by the Indian company ECIL (Electronics Corporation of India Limited). Up to now three 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) are closed.

118 power converters for quadrupoles (5 types) and 50 power converters for steerers (2 types) were already manufactured, successfully tested and shipped to FAIR.

After the successful tests of the FOS power converters, the series production of the remaining units has started. The delivery of all these power converters will be completed in the second half of 2023.

The series production of 53 power converters for dipoles and 8 power converters for quadrupoles by the company Jäger Elektrotechnik GmbH (Germany) is ongoing but affected by to the global supply chain issues. In 2022, a 20kV transformer of a pulsed dipole converter was delivered and the SAT of a FOS power converter was performed at the GSI test facility. The FATs for the first delivery lot was started in the end of 2022 and the delivery of 22 power converters is planned in Q1/2023.

Vacuum chambers

Due to the EU sanctions against Russia, collaboration with the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia, was terminated. At this point all vacuum chambers of batch2&3 (vacuum chambers for dipole, quadrupole and steerer magnets) and batch4 (pumping chambers, bellows, straight tubes, x-cross chamber) were still in the design phase at BINP.

Different strategies for re-procurement of the vacuum chambers were developed and model based cost-estimates were carried out. The design of the chambers was restarted in the construction office at GSI. In parallel, detailed specifications for the different chamber types were updated to fulfill public tendering requirements. A call for tender of the vacuum chambers required to accomplish the FAIR objectives is planned for early 2023.

DOI:10.15120/GSI-2023-00462

Special Installations

The series production of the HEBT Diffusors, which are constituents of the Personnel Access System of FAIR, was started by VA-TEC GmbH & Co KG in 2022. So far, three series devices were delivered to GSI. After that, functional tests on site showed full compliance with the specification and the series production is expected to be completed in 2023.

A contract for manufacturing, testing and delivery of the HEBT18 and HEBT100 beam collimation systems was signed with COMEB S.r.l (Italy). All details on the production process were defined during the FDR, so the delivery of the first of series product is expected for 2023.

As one of the first beamline elements of FAIR, the installation of the graphite core of the HEBT beam dump in the injection beam line for SIS100 was planned and prepared in detail. Installation will be conducted as soon as the building section is committed to FAIR. The graphite core of the HEBT beam dump located in the extraction beam line of SIS100 was ordered from CGT Carbon GmbH. Delivery and installation are planned for 2023.

Special Stands

The FDR for the large support frame (Kraftanlagen Heidelberg GmbH) in building H0705A was carried out in 2022. Finalisation of remaining design issues is planned for early 2023, followed by release for production. Regarding the modular stands for HEBT, 26 of 37 frames of the first group were delivered in summer 2022 by Nordisk Industrioptimering AB (Sweden)/BLEICHERT AUTOMATION GmbH Co.KG (Germany). Further 8 passed the FDR and 3 the CDR. Moreover, a second contract, comprising another 63 frames (group 2+3), was signed in May 2022 with the same companies and the design phase was started.

Dept. Electric Power System (EPS)

Author: Horst Welker

Machine cable management and User Cable

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

Latest update of cable data was provided to Fair Site & Building for the processes of procurement of user cables, as well as for the cable routing and design of machine trays.

At the end of 2022, through the procurement process, the company Electricity EOOD, Bulgaria, was contracted for the material and laying of the user cables.

The cable manager has a regular fixed communication with the companies for routing, FSB and tray designers, as well as with all the users (departments).

The routing process is ongoing and coordinated together with FSB. The design of machine trays is finished in 4 tunnels and is in progress in another 2 areas/buildings.

For the India In-kind cables, in Q4/2022, the provider assigned and the first kick-off meeting took place. Further steps are the signing of the contract and a visit of the company's factory.

EPS

To ensure a stable and reliable operation of the existing 950 power converters in GSI, several up-grade and refurbishment projects were realized in 2022. More precisely, the renewing of the power parts of the quadrupole power converters for the Fragment Separator using state-of the art components was started. In parallel their analog control systems will be upgraded to digital ones based on the FAIR standards. The same upgrade was done on two steerer power converters for the UNILAC. The old Programmable Logic Controller (PLC) systems of the main power converters of the ESR were exchanged by modern Siemens S7 systems. As a replacement, two new dipole power converters for the LEBT of the UNILAC and 6 new quadrupole power converters for the SHIP experiment were ordered. For both projects the FDR was performed in 2022, in case of the SHIP power converters the FATs were finalized. In general, several re-design activities on existing analog PCBs (like controller boards and driver cards for IGBTs) were done to overcome discontinued components and improvements due to state of the art technologies. An interface card for the digitizer system was developed and is implemented successively in all analog controlled power converters to allow visualization of signals in the control room.

For the Alvarez Upgrade project, a design was made for pulsed power converters. Two converters were built and tested. They will be used at the test facilities of the manufacturers of the corresponding magnets.

Dept. Cryogenics (CRY)

Author: Dr. Holger Kollmus

The technical department Commons Cryogenics (CRY) is responsible for the GSI and FAIR wide cryogenic helium supply of superconducting magnets and cavities. CRY is presently operating 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. Additionally, CRY serves small consumers like the final focusing system of APPA and the large-scale experiments CBM / HADES and Panda.

Furthermore, the department is responsible for the so-called local cryogenics belonging to SIS100 and Super-FRS respectively. In the following different recent activities will be highlighted:

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 now, the plant has about 58.000 h of operation. All 110 SIS100 dipole magnets and all 18 SIS100 current lead pairs were tested so far. In 2021 and 2022, the available SIS100 quadrupole-modules have been tested and the assembly of a string set-up was started. The string test set-up consists of one quadrupole-module and two dipole magnets. They will be cooled down for the first time in 2023. Additionally, the missing dipole-modules have been completely tested in 2022.

Installation of the FAIR Cryo Plant CRYO2 (German GSI In-kind)

Figure 94. Delivery of the cold box CRYO2 to FAIR.

In Q3/2022 the big central Cryo plant CRYO2 was delivered to FAIR. Figure 94 shows the delivery of the cold box with a special heavy-duty transportation truck. In the meanwhile, the cold box and the distribution box DB3 have taken their permanent place. The tubing between the different devices is being ongoing.

Figure 95. Kompressor system for CRYO2 and CWU.

Figure 95shows the compressor system for CRYO2 und CWU, the Cool down a Warm-up Unit for the SuperFRS. One can see 5 compressors: two low pressure (LP) and two high pressure (HP) compressors for the CRYO2 and one single-stage compressor for the CWU. The CWU compressor can be used as a redundancy for either LP or the HP compressors of CYRO2.

The CRYO2 has a cooling capacity of 14 kW @ 4 K and 50 kW @ 50 – 80 K.

Presently, installation is ongoing and the mechanical completion is planned for June 2023. The start of commissioning will follow the availability of high-power electricity and cooling water.

The Cryogenic Distribution System

Figure 96. Part of the distribution system in niche 5.

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, which was assigned as a polish in-kind contribution in 2022. For the SIS100 distribution system all parts were produced until early summer 2022. The installation has started in October 2022, scheduled to be finished one year later in October 2023. Figure 96 shows a part of the distribution system during installation, showing the DB4 distribution box and the transfer lines to the feed box of SIS100 in niche 5. The installation is progressing very well within the time schedule, even though the amount of companies currently working in parallel inside the SIS100 tunnel require a huge coordination effort.

Dept. Transport and Installation (TRI)

Author: Mario Bevcic

TRI supports the Accelerator Operation Division in service, reconstruction and upgrade of GSI-accelerator components during the shutdown 2022 and for preparing the planned beam time program,. Moreover, TRI is, together with the Sub-Project Site Management, strongly involved in the development of transportation and installation concepts, tools and special devices for the FAIR Accelerator components.

Other aspects in focus are the preassembly and preparation of already supplied FAIR components, especially magnets for SFRS and the support of testing and the preassembly of SCM Magnets for SIS100.

Dept.: Vacuum Systems (VAC)

Author: Andreas Krämer

As planned in the framework of the FAIR project, the specification and procurement of standard vacuum components like controllers for vacuum pumps and gauges have been continued in 2022. The contracts for the delivery of controllers for ion getter pumps with company Agilent Technologies and for controllers of NEG pumps with company SAES Getters SpA were signed. Moreover, a contract for delivery of controllers for vacuum gauge of type Extractor with company Prevac SP.ZO.O. was closed.

In addition, VAC supported the other subprojects in continuing the vacuum system design and delivering the required information for the civil construction, like cables types and allocation of components. Further, VAC is involved in the ongoing tests of cryogenic magnet modules of SIS100 at the series test facility.

In 2022, vacuum acceptance tests on about 120 vacuum chambers and components were conducted in the vacuum laboratory. These tests are the necessary quality control measures in order to guarantee the required vacuum levels at FAIR and GSI. Only components that have passed these tests are accepted to be installed at FAIR and GSI. Among the tested components were SIS100 standard pumping chambers, HEBT beam diagnostic chambers of different manufacturers, SIS100&HEBT BPMs, SFRS slit systems, SFRS Multipletts, components for experiments in ESR & CRYRING and various material samples.

Beside these tasks, the department VAC operates the vacuum systems of the existing GSI accelerators and supported the Accelerator Operation Division with personal in the main control room during beam time. All this effort is an essential piece of the big puzzle for the successful beam time campaign in 2022.

VAC will also focus his efforts on the routine maintenance of the vacuum systems of GSI and their components during the ongoing shutdown 2022/23 and on the reconstruction and upgrade measures for GSI systems, like ea. upgrade of the vacuum control system to FAIR standards of the transfer channel (TK).

11. Research in targets, detectors, electronics and IT

Research on novel accelerators, detectors systems, read-out electronic and IT are summarized in the programme "Matter and Technology". At GSI several departments are contributing with their research activities to this topic. Not all activities are listed in this section. Research on recent achievements in laser plasma acceleration are described in the contribution of the Plasma Physics department and the status of the design and construction of a novel superconducting cw linear accelerator are outlined in the section of "Accelerator operations".

11.1 Activities of the Department Target Laboratory

Head: Bettina Lommel
Autors: Bettina Lommel, Elif Celik Ayik, Annett Hübner, Birgit Kindler, Jutta Steiner, Vera Yakusheva

The target laboratory of GSI and FAIR produces dominantly targets from stable materials in our conventional lab.

Additionally, we process natural uranium and ^{238}U, which is depleted in ^{235}U, to reduce the level of radioactivity. For this material, the production processes are adapted from the deposition of stable materials. The preparation takes place in a radiation surveillance area. Precautions have to be taken according to radioactive material and heavy metals, so special care on health issues and waste management is needed. Therefore, we equipped the coating plant with an extraction system to protect the operator during mounting and cleaning procedures.

We produce uranium targets on carbon or on metal backings and process metallic uranium or uranium oxide UO_2 both with magnetron sputtering, additionally UF_4 can be produced with thermal evaporation.

For this purpose, we have a coating plant available, which is equipped with a 1-inch circular DC magnetron-sputtering source as well as water-cooled electrode connections for thermal evaporation from a boat or a crucible. We produce UO_2-Targets in a large thickness variety from tens of µg/cm² up to more than 1 mg/cm² on carbon backing.

Several uranium and uranium oxide targets were produced for the GSI SHE physics group for different experiments and collaborations.

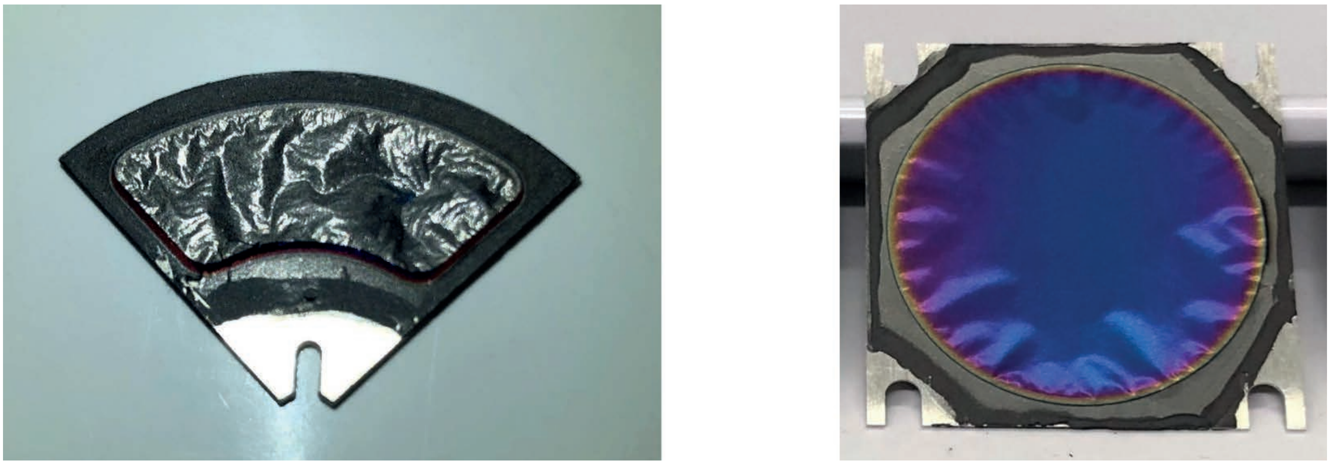

Figure 97. Left – Metallic uranium with 360 µg/cm² on 40 µg/cm² carbon backing; Right - UO_2 with 100 µg/cm² (based on U) on 50 µg/cm² carbon backing.

We produced metallic uranium on special frames (see Figure 97 left) for studies of multinucleon transfer reaction with the goal to produce new heavy exotic isotopes. Multinucleon transfer products in Xe + U collisions will be studied, where the specific interest is to study production yields of transfer products in the uranium and transuranium region. The experiments take place at Argonne National Lab, USA.

UO_2-targets were produced to study the not-yet-fully explored dynamics of the multi-nucleon transfer at the MARA separator at University of Jyväskylä, Finland, by GSI-JYFL collaboration. One of the targets is shown in Figure 97 right.

For a collaboration with IFIN-HH in Bucharest, UO_2-targets were requested for two different projects. One experiment aims at the synthesis of rather neutron-rich super-heavy isotopes through alpha particle evaporation from low-excited super-heavy compound nuclei. Among other, collisions of $^{48}Ca+^{238}U$ will be investigated. In a second experiment, uranium targets are used for collisions of protons with uranium. Aim of the experiment is the study of symmetric and asymmetric fission of $^{239}Pu^*$ nuclei as a function of beam energy.

11.2 Activities of the Department Experiment Electronics

Head: Dr. T. Bretz (GSI)
Authors: T. Bretz, H. Brand, H. Flemming, K. Koch, N. Kurz, M. Traxler

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 new 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 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. After data acquisition, the GO4 analysis 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. Various such control systems, mostly based on LabVIEW, C++ and Python, are offered. In addition to common large-scale systems, Experimental Electronics provides support and solutions for everyday challenges in facilities and laboratory setups.

Highlights

Development of a low-cost, high-performance spectral pulser

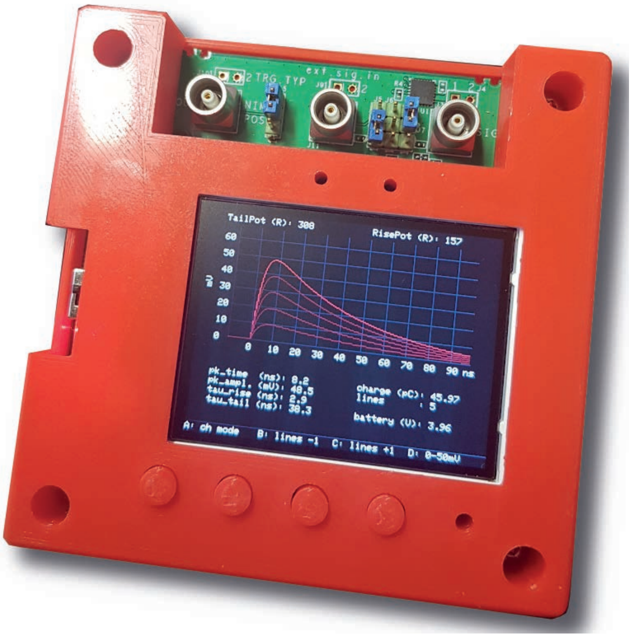

Figure 98. Pulser.

In many experiments or laboratory setups, artificial ultrafast pulses similar to pulses from e.g. photomultipliers (PMT) or other detectors are needed. A powerful but inexpensive spectral pulser has been developed for testing in the absence of real signals from these detectors (see Figure 98). The pulser provides signals of both polarities up to 500 mV, which are very similar to PMT pulses. The peak time is adjustable in the range of two nanoseconds to 30 ns, while the decay constant is in the range of three nanoseconds to 110 ns. Optionally, the pulser can generate a comb spectrum and implements a simple pseudo-random number generator. A preview image shows the pulse characteristics on the display as well as the numerical values of the pulse. The device is battery powered and rechargeable via USB, so that a potential-free adaptation to the subsequent electronics is given.

Application of the laser cutting system

In 2021, a new professional laser cutting system was installed in the EEL laboratory. It successfully fulfills its original purpose to cut printed circuit boards into unusual shape and enable cuts that are particularly close to the printed circuit and its soldered components. It turned out that the device can be used for other purposes as well. Several other tasks were successfully investigated and performed. To complete tests as planned, cutting very clean and accurate shapes in ceramic insulators for the SIS100 magnetic current leads was developed and performed under high time pressure, creating very small holes (~50 μm) in foils for targets. A method for cutting 400 μm thick thermal pyrolytic graphite was also developed. Special stencils for applying solder paste are needed for mounting electrical components on printed circuit boards. It has been shown that the laser cutter can be utilized for their production. This helps to shorten development cycles in the prototyping phase.

CBM-TOF front-end electronics for STAR@BNL

The STAR experiment at Brookhaven National Laboratory (BNL) aims to study the formation and properties of the quark-gluon plasma (QGP), a state of matter that is thought to exist at sufficiently high energy density. In collaboration with the STAR experiment, Experiment Electronics has adapted the front-end electronics developed for the CBM time-of-flight (TOF) detector to their needs. Testing at BNL showed excellent performance, but also revealed that the electronics could be damaged by unexpected overvoltage spikes in the experiment environment. As a solution, a very robust input protection had to be developed and successfully tested to withstand these overvoltage spikes.

Successful test of DiRICH5s1 modules

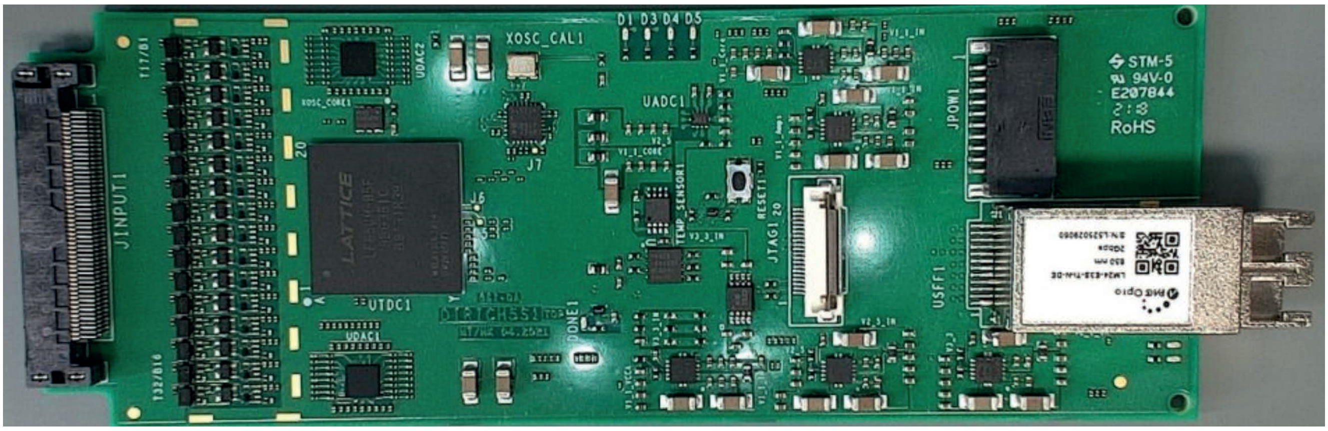

Figure 99. DiRICH5s1.

DiRICH is a compact electronics system designed for reading micro-channel plate (MCP) and multi-anode (MA) PMTs at CBM, PANDA, and HADES. The Figure 99 shows a module that provides amplification, discrimination, digitization, and data acquisition for six MA-PMTs (384 channels). For time-to-digital conversion (TDC), the module uses a field-programmable gate array (FPGA) with a special TDC-core gateware (FPGA firmware) also developed by Experiment Electronics. It achieves a timing accuracy of twelve picoseconds (RMS between two channels for analog 20 mV pulses at 50 Ω).

The DiRICH5s1 module (Figure 99) has been successfully fabricated and used in a low-gain avalanche detector (LGAD) based start-time and beam monitoring system during a beam time at the Darmstadt Superconducting Linear Accelerator (S-DALINAC). The DiRICH5s1 is a stand-alone 32-channel high-precision TDC system (~10 ps RMS between two channels, LVDS input). The connection to the data acquisition system is realized via an optical cable. This allows for a very flexible mechanical setup, depending on the particular spatial requirements of the experiment (see Figure 100).

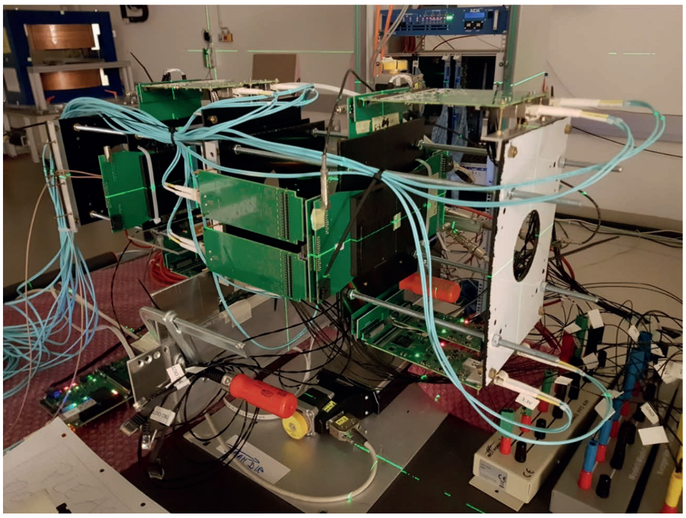

Figure 100. DiRICH Mechanics

Readout of 6000 SiPMs for WASA-FRS HypHI

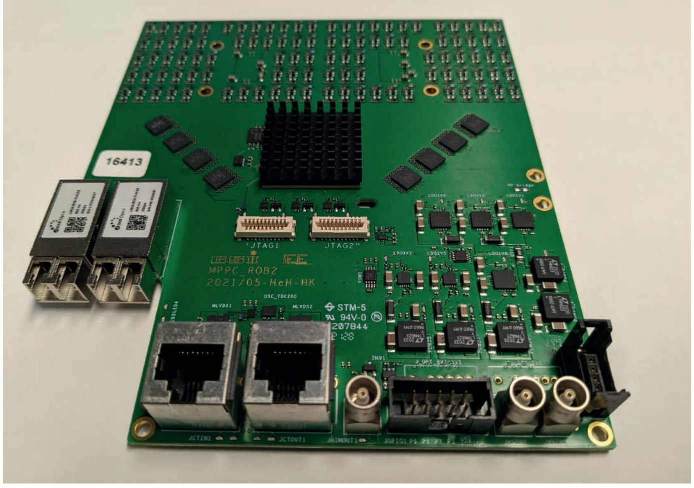

Figure 101. MPPC_ROB2

The Wide Angle Shower Apparatus (WASA) was developed to produce and study so-called hypernuclei at the Fragment Separator (FRS) during FAIR phase 0. To this end, the HypHI (Hypernuclei Production with Heavy Ions) experiment, previously operated at GSI/FAIR, is now operated in combination with WASA and the FRS to achieve higher detection efficiency. In the 2022 beam-time, WASA-FRS HypHI successfully performed readout of nearly 6000 channels using silicon photomultipliers (SiPM) for photon detection. An MBS-based data acquisition system and a specially designed readout board (MPPC_ROB2) were developed for that readout. The data acquisition system was fabricated and implemented by Experiment Electronics. The MPPC_ROB2 is a 128-channel amplifier with FPGA discriminator and 170 ps FPGA-based TDC system, both developed in the EEL department (see Figure 101).

ASIC development and a new precision ASIC TDC

Large applications often require the development of application-specific integrated circuits (ASIC) to keep an excessive number of readout channels affordable. The ASIC development group is currently working on three projects: In 2022, prototypes were fabricated in a low-cost 180 nm CMOS technology for the design study of an improved TDC architecture. Initial characterizations show excellent single-channel timing accuracy of less than 7.5 ps. For beam diagnostics in FAIR, some important improvements were made to the wide dynamic range preamplifier AWACS, and finally, prototypes of the ATR16 and CTR16 transient recorders destined for PANDA and SFRS were post-processed and prepared for characterization. To keep pace with the ever-increasing requirements of FAIR experiments, initial steps were taken to apply smaller and thus faster 65 nm technology.

LabVIEW

LabVIEW (a National Instruments brand: NI) is an integrated development environment with a feature-rich graphical programming language. This enables fast and easy development of production systems for test and measurement purposes. In this context, LabVIEW applications are developed and supported by Experiment Electronics and used in a variety of small and large projects at GSI/FAIR. Well-known customers are PHELIX and SHIPTRAP. The SHIPTRAP ion trap facility at GSI was established to enable precision experiments with very heavy ions produced in the SHIP velocity filter, which are known for the search and discovery of superheavy elements. The LabVIEW-based control system of SHIPTRAP has been further improved and is now nearly complete. The improvement includes an updated driver for phase imaging ion cyclotron resonance (PI-ICR) measurement, which can now run on Windows 10. Similar control systems have been set up and modified for the PUMA experiment at TU Darmstadt and for MLLTRAP in Orsay.

Recent changes in NI's licensing terms, more generally the Enterprise Agreement with the Helmholtz Association, raise concerns of a significant and disproportionate cost increase in the near future and required a careful evaluation of current and future applications, possible alternatives and potential exit scenarios.

With contributions to the Experimental Physics and Industrial Control System (EPICS), Experiment Electronics is involved in the development of a powerful alternative that will be used, for example, in the detector control system of the HADES experiment, for which EEL is responsible for coordination, development and maintenance. In this context, a new magnetic control system (MCS) has been developed and is expected to be operational in spring 2023. However, EPICS, which aims to provide a real-time distributed control system for large scientific instruments, may be too complex for small or medium-sized experiments. As an alternative for these experiments, Experiment Electronics is developing a Python-based alternative. The choice of Python has many undeniable and obvious advantages, such as.

- Open source, available on many platforms, supported by most IDEs.
- Large number of third-party packages, e.g. GUI bindings such as Qt or TK.
- Many hardware vendors offer Python wrappers for their device drivers
- Performance or safety critical algorithms implemented in other languages, such as C/C++, can be wrapped in Python.
- Python is very popular in our community and part of the curriculum at most universities.

For existing LabVIEW applications at GSI while use the CS/CS++ framework that was developed by Experiment Electronics, a possible migration path to a Python framework was demonstrated. The demonstrator was implemented using the pykka framework, which implements the so-called actor model. Furthermore, MQTT was utilized as for simple network communication. The actor model introduces some simple rules to control state sharing and collaboration between execution units for easy implementation of concurrent applications. MQTT is an open and lightweight network protocol based on a queuing system. It is designed for connections with remote sites that have devices with limited resources or network bandwidth. Based on such a Python front-end, a control and measurement application was developed to replace LabVIEW for a prototype of a flexible multichannel pattern generator with a TDC system. This development took place in cooperation with SHIP and SHIPTRAP. Interest has also been expressed by other parties.

11.3 Activities at the Department Detector Laboratory

Head: Dr. Christian Schmidt (GSI)
Author: Christian Schmidt

Activities at the detector are continuing in their focus towards the completion of FAIR detector systems and support for beam times within the FAIR Phase-0 program.

A dedicated production batch of LGAD sensors produced at Fondazione Bruno Kessler (FBK) has successfully been tested and fully characterized for different applications [1][2], including the reaction time detector for the High Acceptance Di-Electron Spectrometer (HADES) at GSI in Darmstadt, Germany, a beam-structure monitor for the Superconducting Darmstadt LINear Accelerator (S-DLINAC) at Technische Universität Darmstadt [3] and an ion imaging experiment conducted at the MedAustron cancer therapy and research center in Wiener Neustadt, Austria. A dedicated telescope consisting of 4 LGAD stations has been constructed and employed in several experiments

At mCBM, the FAIR Phase-0 test and validation facility for CBM, detector modules of the CBM Silicon Tracking System (STS) have successfully been tested with several modules in concert in a real particle tracking configuration. Tracking of secondary particles could for the first time be realized all the way back to the heavy ion interaction point. This important achievement for the CBM-STS also verifies that module serial production is feasible at DTL, one of the two STS detector module assembly sites. Module assembly capability could further be demonstrated through the pilot production of 10 CBM-STS modules and ladders that will be used as tracking detectors of ultra-low material budget in the E16 experiment at J-PARC for the study of spectral changes of vector mesons in cold nuclear matter using e^+ e- inv. mass [4]. The preparation for the CBM-STS serial assembly activity is a mayor activity at DTL and may be considered an extended engagement for the CBM-STS.

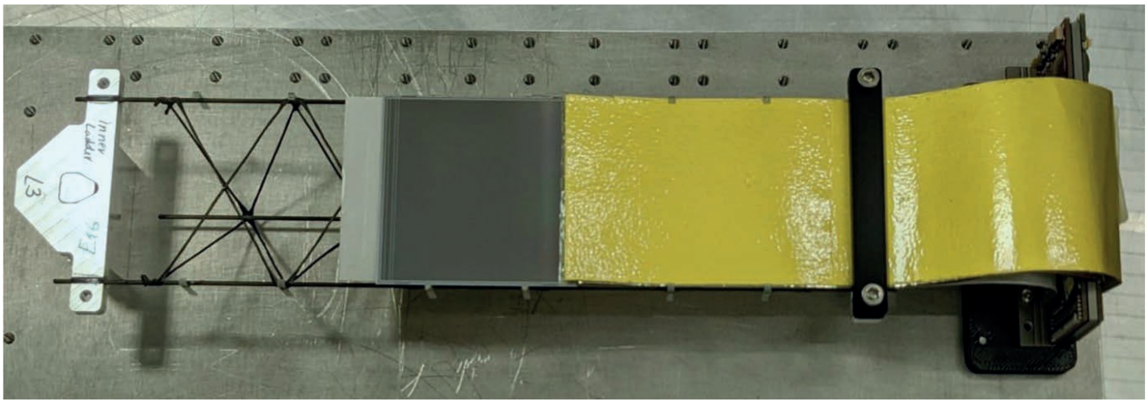

Figure 102. One individual sensor module mounted on a fiber carbon structure for the experiment E16 at J-PARC.

DTL participates in the developments for CMOS pixel sensor integration. To this end ALPIDE- [5] but also MIMOSIS-sensors have been integrated and worked with. Whereas MIMOSIS will be the key monolithic active pixel sensor device for the CBM-MVD, various other applications aim to employ the available ALPIDE-sensor for their goals. Eventually the aim is to assemble waver-scaled versions of such sensors in a self-supported, bent configuration for ALICE ITS3 and potentially also in future upgraded instruments at FAIR.

Beyond CBM-STS the bonding laboratory continues supporting the project STRASSE and its prototyping project PFAD (orchestrated by Prof. Obertelli of TU Darmstadt) as a Silicon Tracker for Quasi-free Scattering Measurements at the RIBF facility of the RIKEN Nishina center [6].

After the successful tests of MIMOSIS-I for radiation tolerance and performance, the prototype CMOS pixel sensor for the CBM Micro Vertex Detector (MVD) could be launched for production in its close to final version by the designing laboratory IPHC in Strasbourg. These activities were important contributions to the EU program EURIZON.

The construction of several Multi Sampling Ionization Chambers serving the need for standardized energy-loss measurements at the Super Fragment Separator focal planes is being continued as Finnish in-kind contribution to FAIR, which GSI was contracted for.

In a collaborative activity between Detector Laboratory and the department Beam-Diagnostics Instrumentation, a combined CG (Current Grid) + IC (Ionization Chamber) detector assembly is being assembled in a serial production of 40 devices. These devices will serve to measure the beam profile and intensity at the FAIR High Energy Beam Transport beamlines (HEBT).

For the AMBER collaboration, a new Active Target Chamber could be tendered. The detector laboratory is involved here in the design and production of novel, ultra-low mass carbon fiber based beam windows that can withstand the test pressure of 32 bar.

Together with the R3B and the SuperFRS collaboration, new large-area silicon micro-strip detectors were built and tested. Originally developed at INFN Perugia, these detectors allow particle ID and tracking at higher particle rates and larger angular coverage as it was possible before. After test experiments at COSY (FZ Jülich) using a proton beam with different energies, 10 detectors of this type were employed in two experiments within the R3B setup.

A prototype of the field cage for the HYDRA-TPC with MICROMEGAS for use at the R3B GLAD magnet has been developed and is currently being tested. To this end, also research with new Spark-Less Amplification Microstructures (SLAM) as well as DLC-coated Thick-GEMs in a study of stability against electrical discharge as a part of the RD51 collaboration has been realized.

For the construction and operation of gas-based detectors in physics experiments, it is important to examine the materials required for the construction of the detector for their outgassing behavior and any resulting aging phenomena in the detector and thus to counteract this. For this purpose, a test setup is available in the detector laboratory which allows to investigate and characterize this ageing behavior of materials in gas detectors. As special feature two different materials can be tested in parallel for their outgassing behavior. After completion of a measurement campaign, the measurement detectors are replaced by a new set of detectors. All parts in contact with contaminants, gas hoses and tubes as well as the outgassing container are then intensively cleaned or replaced in preparation for the next test.

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11.4 Research Data Management at GSI/FAIR 2022

Head and author: Andrew K. Mistry

Increasing the accessibility and availability of research data to external communities under the umbrella of Open Science offers numerous advantages, including fostering citizen science, promoting collaboration, and enhancing the visibility of research and, by extension, the researchers. Research data management (RDM) facilitates this by ensuring that data follow a path of intentional organisation, from the initial conception of a project, through data collection and analysis, and finally to dissemination of the results and long-term storage of the supporting information. In addition, RDM promotes data quality and enables reuse, both internally and externally.

Interest in the concept of open data is expanding rapidly, nationally and internationally, and concrete actions are being taken that directly impact GSI and FAIR. From 2023, the Helmholtz PoF IV mandates that centres and institutes report the number of published data items as a metric in support of these ongoing developments. GSI and FAIR are actively implementing RDM practices and tools towards a system that conforms to the Guiding Principles of Findable, Accessible, Interoperable, and Reusable principles [DOI:10.1038/sdata.2016.18]. This effort aligns to RDM and Open Science policies from, for example, Helmholtz [DOI:10.48440/os.helmholtz.056], and the DFG [DOI:10.5281/zenodo.6472827].

In an effort to provide enhanced benefits to our institutions and beyond, GSI and FAIR are actively engaged with several open science projects on a national and international level including PUNCH4NFDI, EOSC, EuroLabs, and ESCAPE.

To achieve the goals of open data and concurrently support sound RDM practices, a coordinator for RDM for GSI and FAIR was employed in March 2022, with a background in research and experience in working at the facilities. The targets are to conceptualise RDM, and most importantly, ensure that researchers are informed and have the necessary tools and information. In 2022, the first concrete steps were taken as discussed below.

An RDM policy and a broader guidelines document were prepared and will soon be made available. These state the goals of RDM at GSI/FAIR, while highlighting the support provided to researchers in the application of RDM. In addition to providing clarity on the steps involved with data management, the documents also suggest best practices in the field and invite the researchers to consult with the RDM coordinator.

As communication in RDM is crucial, a webpage hosted on the GSI website containing all relevant material (including other Open Science aspects) is now available.

A GSI/FAIR Open Science Working Group was established comprising representatives from the scientific-technical council, the library and documentation group, the grant office, IT group, technology transfer and other interested parties. The group convenes once per month to discuss and share ideas, follow updates on Open Science and to provide support and input to the various topics.

A thematic workshop on RDM at GSI was hosted in July 2022. RDM was introduced; requirements and support were explained by the grant office; the Helmholtz Open Science office explained their role; and presentations from individual research groups highlighted the diverse data structures they work with. A lively discussion period enabled researchers to receive information on how RDM will be applied going forward, and to give feedback. The workshop will be expanded in 2023 to include a broader range of Open Science topics.

A questionnaire for researchers on RDM was distributed to all research groups at GSI. The aim was to obtain an overview of RDM practices currently in force, and what areas to address in the near future. The results indicated that more information will be required on planning and practices across the board.

A Data Management Plan (DMP), a strategic document outlining RDM in a project, will become obligatory for all research projects at GSI and FAIR in the longer term future. Data Management Plan templates are available from the GSI Open Science Webpage, and a preparation tool is under development.

A strategy to publish data in external repositories was drawn up. Instructions and the workflow are now available to do this, and researchers are encouraged to think of what data they intend to publish. As a longer term goal, a new research data repository will be offered to researchers to enhance the publication of research data.

DOI:10.15120/GSI-2023-00462

11.5 Research of the IT Department

Head: Prof. Dr. Thorsten Kollegger (GSI & Johann Wolfgang Goethe-University)
Authors: Mohammad Al-Turany

The IT Department provides the IT infrastructure required for the fulfilment of the GSI/FAIR mission in an efficient and effective manner through building world-class competencies in the technical analysis, design, implementation, operation and support of computing infrastructure and services.

Cluster

Cluster group has created a hardware prototype of the next deployment version of Virgo cluster. It consists of 2 service and 13 batch nodes and runs Rocky Linux 8. Slurm, OpenMPI, python and other packages from the software stack for Virgo 2.0 were upgraded to more recent versions. First tests with MPI on this prototype were performed successfully.

A dedicated subset of batch nodes served as the test system for preparations for the upcoming InfiniBand upgrade to HDR fabric, migration from CentOS 7 to RHEL 8 as base OS and testing Slurm deployment on CVMFS. A new version of the cluster management and job scheduling system SLURM (Simple Linux Utility for Resource Management) was tested on the subset of batch nodes. This version enables the Advanced Power Management (APM), which puts nodes into a low-power state when they are not in use. This system will go into production in the next version of the cluster (planned for the first quarter of 2023).

MPI benchmark tests which run as CI each time before a container is deployed on CVMFS for public usage were enhanced and extended. In cooperation with Plasma Physics group of GSI a dedicated MPI based converter for EPOCH simulation code was developed and used in production runs to convert EPOCH SDF format to HDF5.

ALICE Grid Framework was upgraded from AliEn to JAliEn.

Storage

The File Storage Queue (FSQ) tool has been extended with a command line tool that enables the users to test the file transfer between their DAQ systems and the Lustre storage system without changing their DAQ software API. The tool is ready for use and has been tested in the last HADES beam time this year. Moreover, the monitoring of the Lustre file system was greatly enhanced, allowing to search for causes and possible misuse and malfunction.

Software development

The tools developed at GSI for the future FAIR experiments and ALICE () where successfully used during the beam time at CERN. The Online Device Controller package (ODC) has been used to deploy and control ~70000 user tasks on 200 nodes during the data taken. The New Slurm plugin allows developed at GSI allows deploying on Slurm-controlled clusters. During the beam time several new features have been added to allow more flexibility, such as sharing of nodes based on the number of cores requirement. Furthermore, the controller now allows partial failures of subsets on the running setup, while continuing operation according to user specification. Additionally, error handling and reporting was significantly improved and accelerated. In online reconstruction part (FairMQ Package) several improvements have been done on the side of the Shared Memory transport. APIs for external creation of memory regions have been extended and improved, while the initialization process has been optimized.

11.6 Activities in technology transfer at GSI and FAIR

Head: Dr. Tobias Engert (GSI)
Authors: Tobias Engert, Yvonne Leifels

For the GSI, knowledge and technology transfer means, on the one hand, the communication of research results to society, politics and the economy; on the other hand, knowledge and technology transfer provide additional value to the current strategic goals of the center. The central goal of GSI's technology transfer strategy is to increase the social benefit of scientific results and technologies. Its measures focus on the technical utilization and commercial exploitation of scientific results from research and technological developments from the operation of the accelerator and experimental facilities.

The transfer strategy pursues three main goals:

1. Creating a culture of innovation by promoting an awareness and understanding of transfer options.
2. Optimisation and strengthening of transfer activities, creation of an effective transfer structure using adequate resources.
3. Development of indicators and monitoring of transfer activities to analyse the impact of transfer instruments.

Innovation Fund and Innovation Board

The GSI/FAIR innovation fund is an essential instrument for supporting technology transfer and establishing effective transfer structures at GSI and FAIR. It is used in particular to finance the product-oriented validation and further development of market-relevant technologies stemming from R&D at GSI/FAIR. The basic prerequisite for a functioning innovation fund is the sustainable provision of financial resources: As a "seed" fund, the innovation fund is sustainably financed by financial return flows from license reveniews, contract research, sales and services. The internal innovation fund is supplemented by funds raised from the Helmholtz Association (approved December 2021). The first official call for proposals was launched in January 2022.

Parallel to the introduction of the Innovation Fund, a GSI/FAIR Innovation Board was founded in 2021, which is staffed by 14 people from different FAIR/GSI organizational units and bundles the diverse interdisciplinary expertise of GSI/FAIR. The Innovation Board makes decisions on the following topics:

- Recommendations on the use of inventions, patenting of inventions, abandonment or sale of proerty rights as well as exploitation strategies for the respective inventions to the management.
- Recommendation on the use and application of technologies
- Approval of applications to the Innovation Fund
- Recommendation to the Executive Board on applications to the Innovation Fund
- Selection of the annual innovation award

In addition, the Innovation Board advises the GSI management on strategic issues of technology transfer, such as proposing new instruments, methods or incentives to strengthen the culture of innovation. The Innovation Board began its activities in January 2022 with its constituent meeting.

Open X

As part of a BMBF-funded exploratory project on Open Science, the effects of Open Science strategies on the technology transfer activities of German research institutions were investigated together with the HZDR and the IPHT (Leibniz Institute for Photonic Technologies). Approaches to solutions were identified and developed that enable successful knowledge and technology transfer under the framework conditions of Open Science.

This exploratory project is being used to prepare a follow-up research and development application, which has been submitted to BMBF: OPEN TRANSFER - Strategies for the Transfer of Research Results in an Open Science Context. This new project started on 01.10.2022. The aim of the Open Transfer project is to develop and test new methods for better transfer of knowledge and technologies in the context of Open Science and with a differentiated understanding of Open Science and transfer.

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Transfer includes any use of research results outside of scientific applications in form of commerical exploitation, irrespective of any considerations, making them available completely free of charge or by employing hybrid approaches where different or no consideration is required depending of the usage type. In the context of Open Science, this means that both research results already generated under Open Science conditions and those generated in the classic, closed system are considered, but which are to be made accessible under open(er) conditions after a certain point.

Event series "HEPTrepreneurs"

In cooperation with HEPTech and CERN, GSI initiated a digital event series HEPTrepreneurs in April 2021, focusing on topics related to entrepreneurship in HEP (High Energy Physics). In 2022, 5 episodes were held on the following topics:

- Deep Tech Startups
- Best practice of successful start-up/lighthouse projects from the field of HEP.
- How can ideas from science change the world?
- Business Incubators/Startup Campus

Based on the great interest of young scientists, this series of events will be continued in 2023.

HAFIS- Helmholtz Transfer Academy

As a result of the positive experiences and interest of the young scientists in HEPTreneurs, GSI applied together with the transfer offices of the other "Matter Centres" - KIT, HZDR, and FZJ - for the HAFIS Transfer Academy in the framework of the Helmholtz Academy for Intrapreneurship (HAFIS). This Academy will start on 01.04.2023.

The aim of HAFIS is to strengthen entrepreneurial thinking and acting among researchers in order to intensify transfer activities in the Helmholtz Association. To this end, a project-based academy is established in the four centres, which will enable researchers to identify and design innovative transfer projects and ensure the prototypical implementation of these projects. This is intended to promote the transfer culture in the centres. The central goal of the Academy is that the participants form teams in which they learn and test tools of intrapreneurship based on their own projects and develop an intrapreneurial spirit. In this way, about 130 researchers will be empowered over the project period of three years and about 35 transfer projects will be initiated. At the end of the funding period, further Helmholtz Centres will be successively invited to join the Academy.

HAFIS will establish approaches in project-based learning in the Helmholtz Association that have already been applied successfully in companies and university education for many years. The target group are re-searchers (doctoral students, postdocs, scientific employees), who are recruited via the heads of research groups or departments.

HITRIplus

The EU project HITRIplus (Heavy Ion Therapy Research Integration plus) under the leadership of GSI aims at preclinical and clinical research and technology development in cancer treatment with heavy ion beams. Lower costs and new-dimensioned facilities should help to make tumour therapy with ions accessible to more patients and at the same time open up new markets for the European industry.

The Technology Transfer department (TTR) is actively involved in work package 4 "Innovation, technology transfer, industry relation". The aim of this work package is to define and implement a roadmap for the exploitation and industrialization of HITRIplus technologies and innovations. TTR is particularly responsible for technology promotion and the identification of relevant HITRIplus innovations and technologies as well as important industry actors.

Transfer of expertise to industry: Green IT Cube / DIGITAL OPEN LAB

The "Green IT Cube" data centre built for FAIR has six floors. The 6th floor, that is already fully equipped with its technical infrastructure, has 256 water-cooled racks. Funds for the upgrade works in the 3rd and 4th floors were successfully applied for in 2021 as response to an EU REACT funding call via the HMWK. The work will be completed in Q1 2023.

After the upgrade of the 3rd and 4th floors, innovations for energy-efficient high-performance computing, IT R&D software projects and ultra-fast data processing are to be tested and prepared for industrial application together with industry as part of a so-called "DIGITAL OPEN LAB". Various companies such as AMD, intel, Toshiba, Georg Fischer, Henkel, Bender, HEAG but also the Darmstadt University of Applied Sciences, Fraunhofer LBF and the Hessian Centre for Artificial Intelligence "hessian.AI" have already expressed their interest in DIGITAL OPEN LAB. A suitable contract structure is already being worked on.

Networking activities of TTR - European Network HEPTECH

Besides regional and national networking activities, the TTR department is also involved in the European technology transfer network "HEPTech" (High Energy Physics Technology Transfer Network). HEPTech was founded in 2008 as one of the goals of a European High Energy Particle Physics Strategy and currently com-prises 16 international members such as CERN, ESS or ELI. In December 2021, GSI's chairmanship of HEPTech ended by rotation and the coordination of the chairmanship was taken over by STFC - the Science and Technology Facilities Council from the UK; GSI has the mandate of the vice-chairmanship of HEPTech for another year.

12. Annex

All publications of the GSI in the year 2021 and all publications related to GSI's large scale research facilities are listed in the publications database (VDB) at the GSI repository.

12.1 GSI and FAIR committees in the years 2022

Ingo Augustin, FAIR; Karin Füssel, GSI

Director's Board / Geschäftsführung

Prof. Dr. Paolo Giubellino, Dr. Ulrich Breuer, Jörg Blaurock

Shareholder Assembly / Gesellschafterversammlung, GSI

Ingo Pfeil [chair], Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany),
as representative of the Federal Republic of Germany

Stephanie Schinzel, Hessisches Ministerium der Finanzen, Wiesbaden (Germany),
as representative of the State of Hesse in Germany

Marion Mietzner-Leist, Ministerium der Finanzen Rheinland-Pfalz, Mainz (Germany),
as representative of the State of Rhineland-Palatinate in Germany

Klaus Donath, Thüringer Finanzministerium, Erfurt (Germany),
as representative of the State of Thuringia in Germany

Supervisory Board / Aufsichtsrat (AR), GSI

Dr. Volkmar Dietz [chair], Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany)

Dr. Ralph Dieter, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany)

Dr. Ulrike Mattig [vice chair], Hessisches Ministerium für Wissenschaft und Kunst, Wiesbaden (Germany)

Dr. Bernd Ebersold, Thüringer Ministerium für Wirtschaft, Wissenschaft und digitale Gesellschaft, Erfurt (Germany)

Jana Podßuweit, Thüringer Ministerium für Wirtschaft, Wissenschaft und Digitale Gesellschaft, Erfurt (Germany)

Dr. Carola Zimmermann, Ministerium für Wissenschaft und Gesundheit Rheinland-Pfalz, Mainz (Germany)

Dr. Andreas Gerhardt, Ministerium für Wissenschaft und Gesundheit Rheinland-Pfalz, Mainz (Germany)

Prof. Dr. Cornelia Denz, Westfälische Wilhelms-Universität Münster (Germany)

Prof. Dr. Thomas Glasmacher, Facility for Rare Isotope Beams, East Lansing (USA)

Prof. Dr. Thomas Nilsson, Chalmers University of Technology, Göteborg (Sweden), as Vice-Chair of the Joint Scientific Council GSI/FAIR

Dr. Bettina Lommel, GSI Helmholtzzentrum für Schwerionenforschung, as spokesperson of the Scientific-Technical Council of GSI

FAIR Council / Gesellschafterversammlung FAIR

Dr. Volkmar Dietz [chair], Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany)

Dr. Catalin Borcea [vice chair], Horia Hulubei National Institute of Physics and Nuclear Engineering (NIPNE/IFIN-HH) (Romania)

Dr. Andrea Fischer, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany), as representative of the Federal Republic of Germany

Dr. Ulrike Mattig, Hessisches Ministerium für Wissenschaft und Kunst (Germany), as representative of the Federal Republic of Germany

Dr. Vyacheslav Pershukov, Rosatom Nuclear Energy State Corporation, as representative of the Russian Federation

Prof. Dr. Victor Yu. Egorychev, NRC Kurchatov Institute, as representative of the Russian Federation

Prof. Dr. Subhasis Chattopadhyay, Variable Energy Cyclotron Center (VECC), as representative of India

Prof. Dr. Uday Bandyopadhyay, Bose Institute, as representative of India

Katri Huitu, Helsinki Institute of Physics

Johan Holmberg, Swedish Research Council (Vetenskapsrådet), as representatives of the Swedish/Finnish Consortium

Dr. Cornelia Anca Ghinescu, Ministry of Research and Innovation, as representative of Romania

Dr. Ruxandra Popescu, Ministry of Research and Innovation, as representative of Romania

Prof. Dr. Zbigniew Majka, Jagiellonian University Kraków, as representative of Poland

Dr. Mateusz Gazyński, Department of Innovation and Development of the Ministry of Science and High Education, as representative of Poland

Dr. Albin Kralj, Ministry of Education, Science and Sports, as representative of the Republic of Slovenia

Dr. Danielle Gallo, Commissariat à l' Énergie Atomique et aux Energies Alternatives (CEA), as representative of the French shareholder CEA

Dr. Marcella Grasso, Centre National de la Recherche Scientifique (CNRS), as representative of the French shareholder CNRS

Dr. Justin O’Byrne, Science and Technology Facilities Council (STFC-UKRI), as representative of the United Kingdom

Marek Vyšinka, Ministry of Education, Youth and Sports (MSMT), as representative of the Czech Republic

Dr. 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); Michael Rafii, Bundesministerium für Bildung und Forschung (BMBF); Philipp Strauchmann, Bundesministerium für Bildung und Forschung (BMBF); Marco Grumler, Econum Unternehmensberatung GmbH; Mikhail Rychev, NRC Kurchatov Institute; Oleg Patarakin, Rosatom Nuclear Energy State Corporation; Peter Bogdanov, Rosatom Nuclear Energy State Corporation; Victor Varentsov, FAIR; Madhusuden Reddy Nandeni, Counsellor (Sc. & Tech); Rajarshi Ray, Bose Institute; Sanjay Kumar Ghosh, Bose Institute; Sanjeev Kumar Varshney, Department of Science and Technology; Maciej Chorowski, Wrocław University of Science and Technology; Piotr Salabura; Jagiellonian University; Paula Eerola, Helsinki Institute of Physics; Antti Väihkönen, Helsinki Institute of Physics; Thomas Nilsson, Chalmers University of Technology; Ionel Andrei, Extreme Light Infrastructure - NP (ELI-NP); Jacek T. Gierliński, Jagiellonian University Kraków; Paul Indelicato, Sorbonne Université Campus Pierre et Marie Curie; Catarina Sahlberg, Swedish Research Council (Vetenkapsrådet); Örjan Skeppstedt, Stockholm University; Alex C. Mueller, ACM Consult GmbH; Thomas Roser, Brookhaven National Laboratory; Jens Dilling, TRIUMF; Christofas Touramanis, University of Liverpool; Alexander Golubev, JINR

Scienctific Sectretary: Thomas Beier

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Scienctific Sectretary: Thomas Beier

Joint Scientific Council of GSI and FAIR (JSC)

S. Raha [chair FAIR Scientific Council, until April 2022], Bose Institute, Kolkata (India);
P. Indelicato [chair FAIR Scientific Council, from May 2022], Lab. Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, Paris (France);
Th. Nilsson [vice-chair FAIR Scientific Council and chair GSI Scientific Council], Chalmers Univ. of Technology, Göteborg (Sweden);
G. Aarts, Swansea University (United Kingdom); N. Alahari, GANIL, Caen (France); M. Aliotta, University of Edinburgh (UK); F. Azaiez, National Research Foundation, iThemba LABS, Somerset West (South Africa); G. Bollen, Michigan State University (USA); M. J. G. Borge, Institute for the Structure of Matter (IEM), CSIC, Madrid (Spain); E. Elsen, DESY, Hamburg, and Frankfurt Institute for Advances Studies (Germany); B. Erazmus, Subatech Nantes (France); P. Gianotti, INFN Frascati (Italy); E. Lindroth, Stockholm University (Sweden); K. Parodi, Ludwig-Maximilians-University Munich (Germany); P. Rossi, Jefferson Laboratory, Newport News (USA); N. Saito, J-PARC Center, Ibaraki (Japan); R. Tribble, Brookhaven National Laboratory, Upton, NY (USA); Y. P. Viyogi, Variable Energy Cyclotron Centre, Kolkata (India)

Scientific Secretary: Carlo Ewerz

Scientific and Technical Council / Wissenschaftlich-Technischer Rat (WTR), GSI

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Scienctific Secretary: Karin Füssel

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Scienctific Secretary: Ina Schubert

Programme Advisory Committee for Biophysics and Radiobiology (Bio-PAC)

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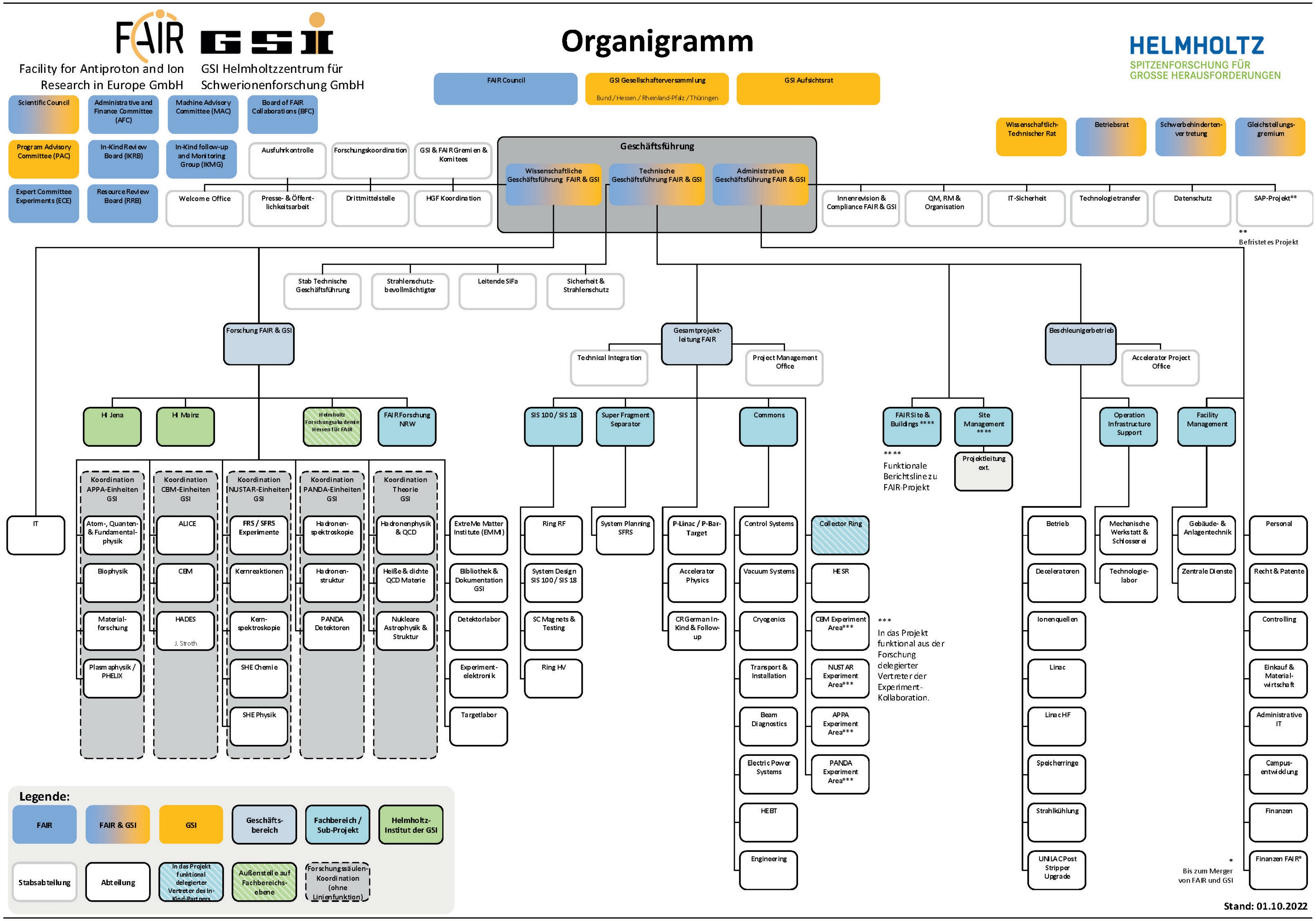
Scienctific Secretary: Karin Füssel

12.2 Organisational chart



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.