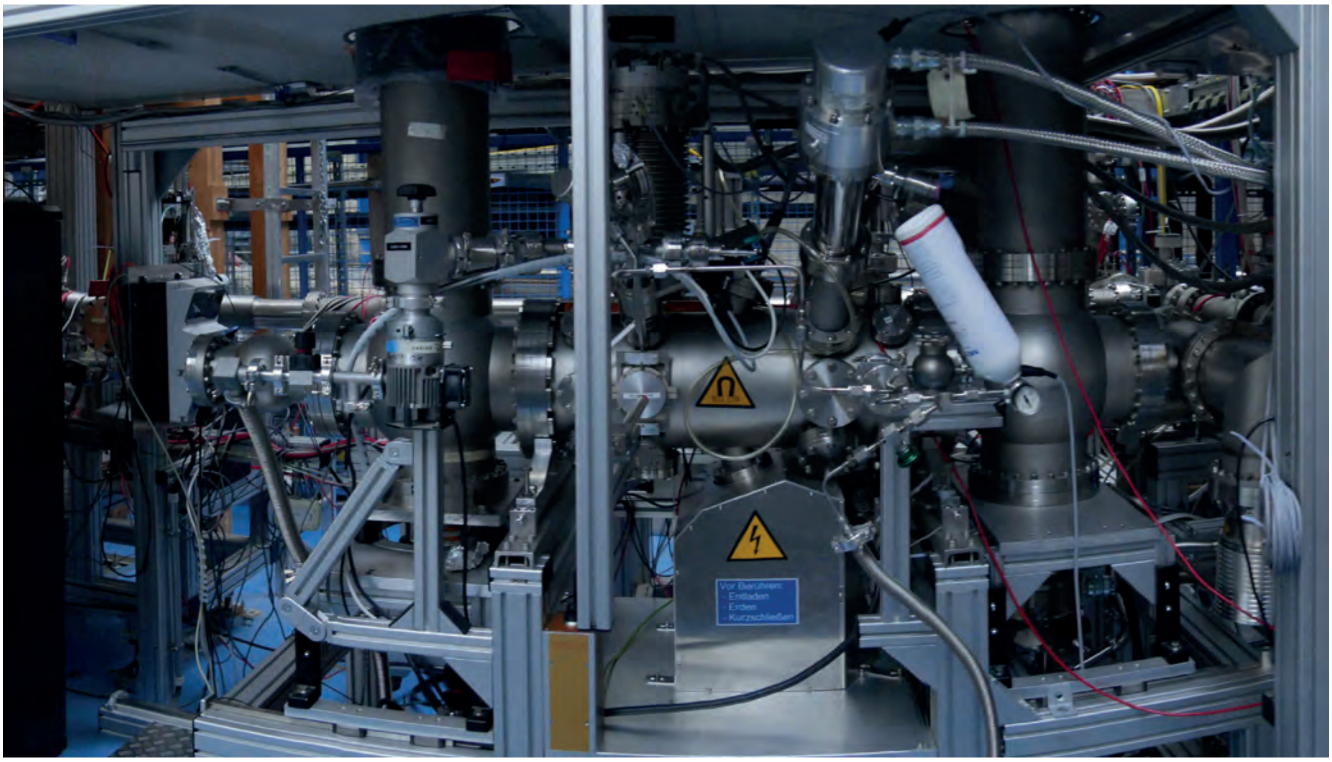
GSI REPORT 2024-1

GSI-FAIR SCIENTIFIC REPORT 2023

An overview of the 2023 achievements in science and technology



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1. Executive summary of research at GSI & FAIR

Coordination: Dr. Yvonne Leifels (GSI)
Author: Yvonne Leifels

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). An overview of the POF IV structure of Matter and the topics to which GSI departments are contributing is shown in Figure 1. Topics, to which GSI departments are contributing are marked in green.

2023 was a very important year for both GSI and FAIR. In March 9/10, the shareholders of FAIR GmbH decided in a special meeting on the progress of the FAIR project. Due to the excellent evaluation in the scientific review of the FAIR project in 2022, the Federal Republic of Germany and the State of Hesse are willing to finance the first construction stage of FAIR with a supplementary sum of approximately 518 million euros. The first construction stage of FAIR, ‘First Science’, will comprise the SIS100, the Super-FRS and the High-Energy NUSTAR cave, where operation of the Super-FRS with SIS18 beams will be an intermediate stage. Despite the difficult global economic and geopolitical conditions, this represents a significant step forward for the research, which will be conducted at FAIR.

25 years ago, GSI together with the Deutsche Krebsforschungszentrum in Heidelberg, DKFZ, and the former Rossendorf Research Center, FZR (now the Helmholtz-Center Dresden Rossendorf), started the clinical radiation treatment of tumors with heavy ions. The initiator of this development was Prof. Gerald Kraft, who established the biophysical department and was leading it from 1981 to 2008. The crucial innovations, which have been established at GSI, were the raster-scanning method, allowing an extremely target-conform irradiation, and the visualization of the irradiated volume by Positron emission tomography (PET). In addition, scientists of GSI and DKFZ developed a method for irradiation planning. Until 2008, 440 patients with tumors in the head and neck were treated successfully.

Research on radiation treatment of tumors is still a very active research topic at GSI. Recently, so-called FLASH conditions could be established at GSI employing the high intensity carbon beam delivered by SIS18. FLASH is a promising new method in tumor therapy. A high dose (i.e. a short, high-intensity ion pulse) is applied to the tumor, thus reducing damage on the surrounding tissue by maintaining the effect on the tumor.

Preparation for the next funding period (POFV lasting from 2028 to 2034) within the Helmholtz Association is ongoing. The strategic discussions on the center level have started. The vision of the GSI/FAIR management is depicted in the concept “FAIR 2028”, which makes the maximum use of the then existing GSI/FAIR facilities including the CBM cave, which is at the moment not guaranteed:

- APPA experiments will take place at the low-energy rings, at SIS100, at the caves at SIS18 and UNILAC with and at PHELIX, In addition, a limited set of experiments could be hosted at all experimental stations served by SIS100
- NUSTAR will perform experiments at the Super-FRS with SIS100, plus SHE and MATS experiments at the UNILAC and ILIMA at the low energy-rings served by SIS18
- CBM will be operated with SIS100 beams, and HADES will continue at SIS18
- PANDA is developing a hadron physics program to be carried as bridge towards the program with antiprotons, when possible using the caves and beams available at GSI and FAIR and employing synergies with other experiments.

Scientific goals and milestones in POFV are presently discussed in various workshops and meetings of the three programs within the research field Matter, Matter and Universe (MU), Matter and Technology (MT), and From Matter to Materials and Life (MML).

Major scientific and technical highlights have been obtained during the last year which will be reported in the following. Here only two will be mentioned: The high-efficient neutron detector NeuLAND which was developed and constructed within the R3B collaboration at FAIR was utilized to measure the four-neutron-decay of the exotic and doubly magic 28O nucleus at the RIBF facility in Japan. In an extensive analysis of the emission spectra of the kilonova observed in 2027 resulting from a neutron star merger it was observed that the ejecta show a spherical emission pattern, which is quite astonishing since the computer simulations of such an event predict aspherical emission spectra.

In summer 2023, GSI and FAIR participated in the roadshow “Universe on Tour” in Hofheim, which was an event in the framework of the “Year of Science 2023 – Our Universe” initiated by the German Federal Ministry of Education and Research (BMBF). GSI and FAIR, the Goethe University Frankfurt and the Technical University Darmstadt presented current research projects. In August 2023, GSI/FAIR invited to the Open House Day 2023. Around 3,500 guests had the opportunity to view research stations, laboratories and experimental setups on the campus in Darmstadt.

The year ended with an engineering run for accelerators and detectors. In 2022, the GSI management decided several measures to deal with the rising costs for electricity/gas and the consequently rising costs for materials and personnel: reduction of the total available user beamtime in the years 2023 to 2025, and shift of the user beamtime 2023 to 2024. A limited number of detector tests were performed. An important milestone was the establishment of dual beam operation for biophysics experiments. Carbon and helium could be provided simultaneously for irradiation experiments. The pion beam capabilities were successfully tested for future experiments at the HADES set-up and at HHT, the plasma physics cave at SIS18, the beam was optimized in preparation of experiments at PRIO and HIHEX. In addition, several detector test were performed by the NUSTAR collaborations.

Many GSI/FAIR scientists received rewards and prizes. Here only a few will be mentioned: Karlheinz Langanke, former Research Director, has been appointed honorary member of the European Physical Society (EPS). The EPS Council decided to elect Karlheinz Langanke to this exceptional circle consisting out of 19 members at the moment, of which 7 are Nobel laureates. Marco Durante, head of the Biophysics Department, has been awarded the prestigious Henry Kaplan Prize by the International Association of Radiation Research (IARR).

The “FAIR-GSI PhD Award 2023” was awarded to Simon Lauber for his doctoral thesis on “Advanced numerical and experimental beam dynamics investigations for the cw-heavy ion linac HELIAC (HElmholtz LInear ACcelerator)”. Within the scope of his thesis work, Simon Lauber made vital and forward-looking contributions, which are of immense importance for the realization of the entire HELIAC project.

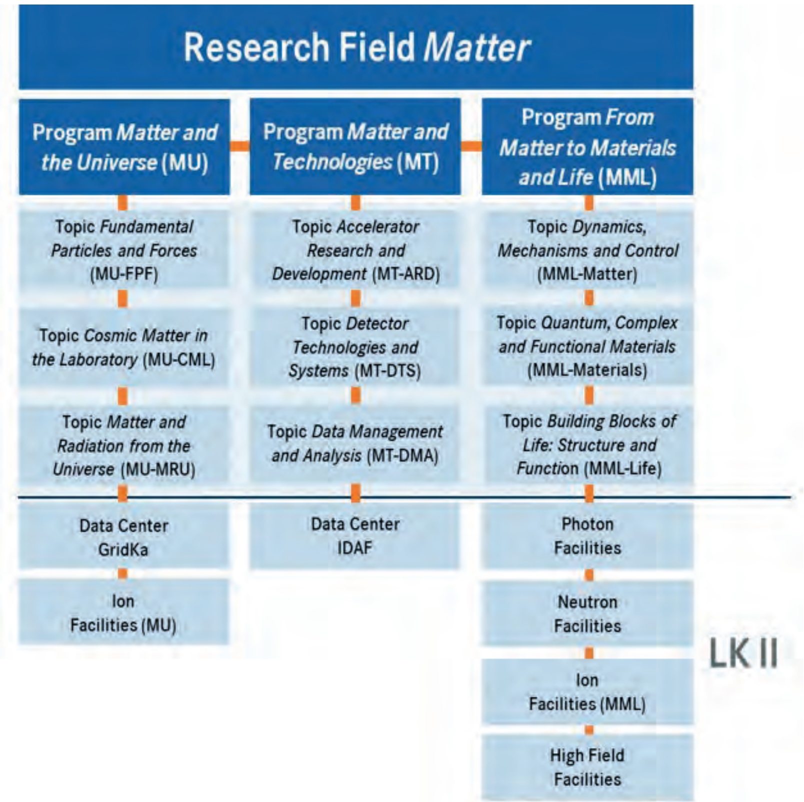
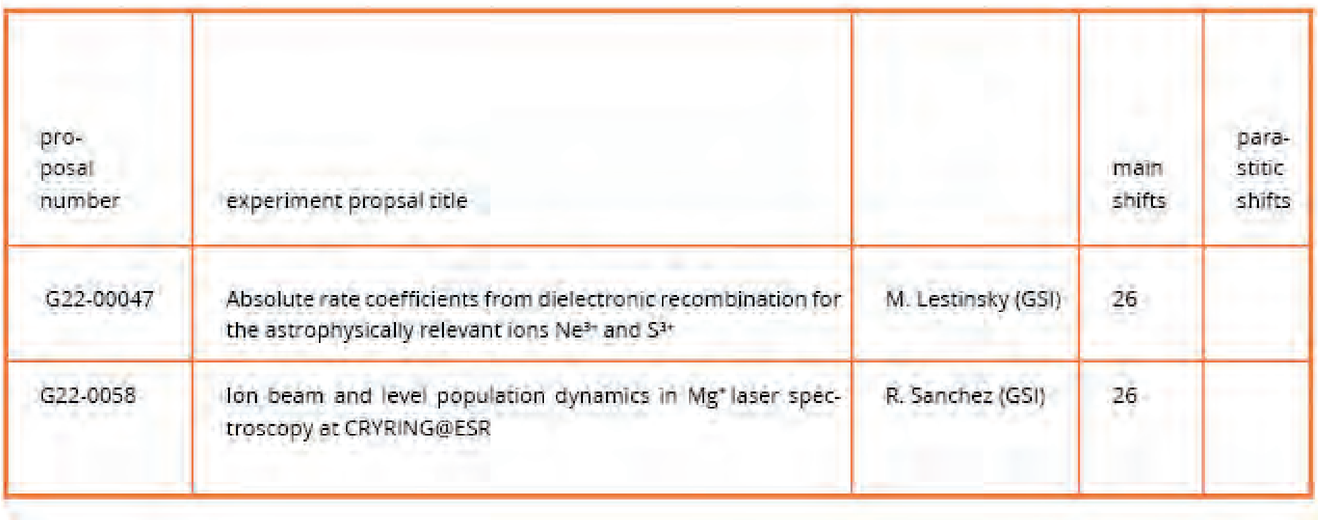


Figure 1. Structure of the Research Field Matter, which is divided into three programs (MU, MT, and MML). Each of the programs comprises three LK1 topics and one or more LKII facilities. GSI is contributing to all topics in MML and MT, and the topic Cosmic Matter in the Laboratory of MU.

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”.

1.1 User beam time 2023

compiled by beamtime coordinator Dr. Daniel Serverin



pro-posal number	experiment propsal title		main shifts	para-stitic shifts
G22-00047	Absolute rate coefficients from dielectronic recombination for the astrophysically relevant ions Ne^{3+} and S^{3+}	M. Lestinsky (GSI)	26	
G22-0058	Ion beam and level population dynamics in Mg^{+} laser spectroscopy at CRYRING@ESR	R. Sanchez (GSI)	26	

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

1.2 Developments for Research Data Management at GSI/FAIR

Author: Andrew K. Mistry

Research Data Management Introduction

The variety and underlying complexity of all forms of data generated and managed at GSI and FAIR, demands good data governance including the management of research data generated in the course of a research project. While in the past research outputs would generally be held closed within an institution, or limited to a collaboration, the movement of Open Science is now rapidly evolving scientific practice into a state where these outputs are made openly available to a broader community.

In Research Data Management (RDM), one of the goals is to ultimately help researchers both in present and future projects by making the data available and the result reproducible in the longer term. Making data open facilitates transparency, knowledge transfer, supports sustainability and acts as a driver for future investigations. In addition, wider societal benefits can result from such practices.

Generated research data at GSI/FAIR should adhere (as best as possible) to the Findable, Accessible, Interoperable, and Reusable (F.A.I.R.)-principles [1]. This requires that the data be placed in a location with a persistent identifier, and also have the necessary software, compute resources and complete descriptions in order for the results stemming from the data to be reproduced. Of course, providing vast compute resources and terabytes of raw data freely to a large audience may not always be feasible (nor particularly useful), hence semi-derived/pre-processed, and result data may also be an option on a case-by-case basis.

RDM@GSI/FAIR: Concepts and Planning

GSI/FAIR is keen to support and encourage researchers in good research data management practices, and developments are now fully underway to aid researchers in making research data openly available with as few barriers as possible. Further information on RDM and Open Science can be found on the webpage [2].

The Open Science Working Group founded in 2022 was formally endorsed by the GSI/FAIR management in 2023. The group meets monthly to discuss latest open science developments, create policies and guidelines, and ensure that open science practices implemented are of benefit to users of the facilities. This includes the development of ideas associated with RDM.

The foundation stones for RDM lie within documentation laying out expectations and promoting the benefits of the practice. The GSI/FAIR policy [3] and Guidelines [4] for RDM were published in 2023. The policy lays the points for practicing RDM, and the guidelines build on this providing more context and offering explicit examples.

RDM within the Helmholtz Community

Within the Helmholtz community, the PoF IV period aims to examine and optimise the methodology behind the open publication of datasets, by counting the number of data outputs within a given institution. While this is a potentially useful benchmark, the F.A.I.R.-principles must also be adhered to as best as reasonably possible. A measure of this can be found for example from developments within the Helmholtz Metadata collaboration, with a dashboard showing not only the number of data publications, but also assigning a score to those data [5]. For the PoF V period, the publication and counting of datasets will become a mandatory procedure for all centres.

Data management planning

Research data management follows a lifecycle (see Figure 3) starting with the planning phase, where the responsibilities, data structure and size, publication and licensing are addressed in a Data Management Plan (DMP). To assist researchers with this, software in the form of an online platform [6] and a template data management plan is now available. This living document should be periodically updated and will support management of data throughout the project lifecycle. It is foreseen that all research projects at GSI/FAIR will have a DMP, and this is already a mandatory requirement of many funding programs.

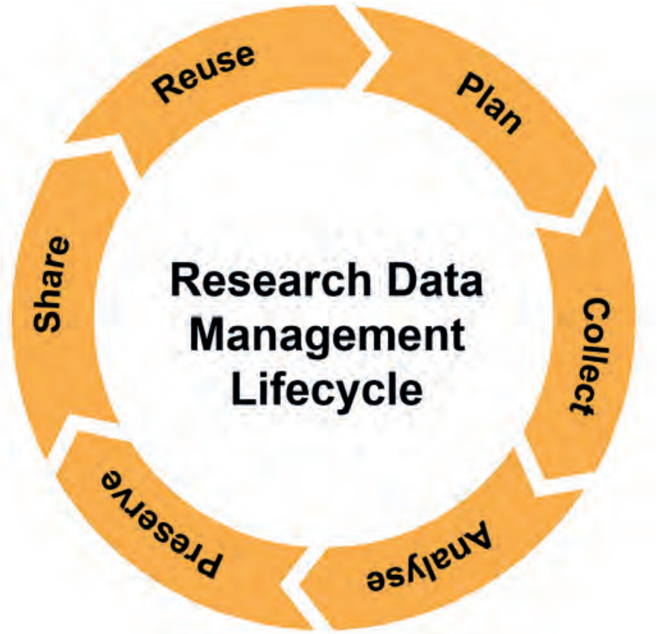


Figure 3. The lifecycle for research data management. Image by A. K. Mistry.

Data publication and recording

The RDM guidelines details the choice when it comes to selecting suitable data publication infrastructures. In addition, there are up-to-date data publication instructions available [7]. The use of the CERN hosted Zenodo repository (in the cases where no disciplinary repository exists) remains as an interim solution, until a GSI/FAIR-wide solution is established. This will likely come in the form of the new GSI MyCore-MIR publications repository under development.

Irrespective of the location of the accessible data, it remains important that a record of the data be generated in the GSI JOIN2 publications repository in a similar fashion to the publication of a journal article.

External open science projects: RDM aspects

There are a number of Open Science related projects and initiatives ongoing at GSI in collaboration with national and international partners.

Within the PUNCH4NFDI project, advances are ongoing in a number of areas. A connection to the lustre file system is under testing for the access and processing of larger volume datasets. A portal to access research data objects will enter a prototype phase in 2024. This will ultimately enable the access, processing, and visualisation of data sets to be done via a web interface, including analysis and workflow provenance.

Within the EuroLabs project, a metadata scheme for nuclear physics experiments is currently in development. This can be completed during an experiment using an online web application, and downloaded in both machine and human readable format. Once completed, this metadata can then be published alongside the dataset. The Helmholtz funded project HELPMI aims to develop a common metadata scheme for the plasma physics community. A workshop to start this project was held at GSI in October 2023.

Communication and events

In October 2023 a workshop for GSI users on "Open Science at GSI/FAIR" was organised by the Open Science Working Group. Here, the current status of RDM at GSI/FAIR including the future plans and ideas were discussed, including contributions from the Helmholtz Open Science office HZDR. The slides can be found here [8].

- [1] Wilkinson, M., Dumontier, M., Aalbersberg, I. et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3, 160018 (2016). DOI:10.1038/sdata.2016.18
- [2] GSI/FAIR Open Science webpage
- [3] GSI/FAIR Research Data Management (RDM) Policy (2023) DOI:10.15120/GSI-2023-00646
- [4] GSI/FAIR Guidelines on Research Data Management (2023) DOI:10.15120/GSI-2023-00916
- [5] HMC Dashboard on Open and FAIR Data in Helmholtz
- [6] GSI/FAIR Research Data Management Organiser https://www.rdmo.gsi.de
- [7] Instructions for uploading and linking research data/software at GSI Helmholtzzentrum für Schwerionenforschung GmbH DOI:10.5281/zenodo.7628019
- [8] GSI/FAIR Open Science workshop 2023 Indico event 17498

2. Research of the APPA Departments

Coordination: Prof. Dr. Thomas Stöhlker (HI Jena, FSU Jena & GSI)

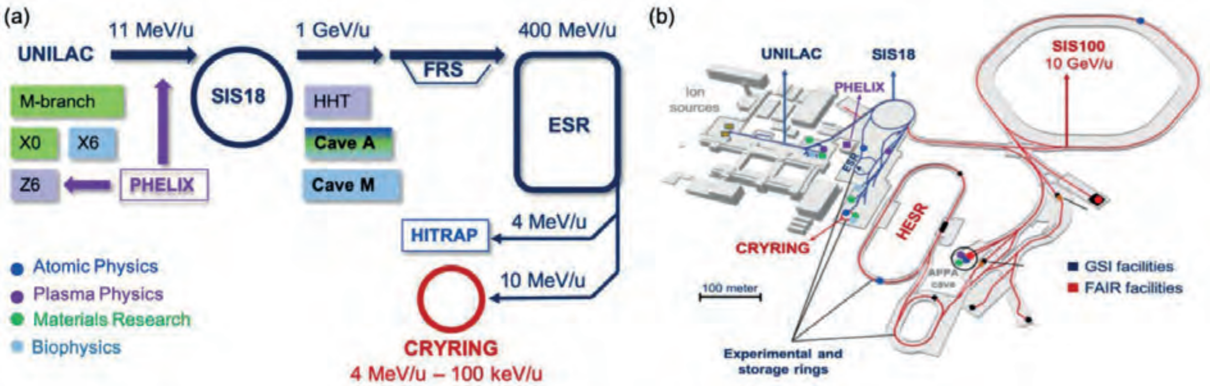


Figure 4. (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (Th. Stöhlker et al., Nucl. Instr. Meth. B 365, 680 (2015)).

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

Figure 4 depicts an overview of experimental stations devoted to MML/APPA physics at GSI and the future FAIR fa-cility whereby all the facilities on the campus of GSI (left side of Figure 4) are in user operation (re-commissioning of HITRAP has started in 2022). Currently, the GSI-MML facilities serve more than 450 users from universities and research institutes in over 30 countries and are the basis of the international APPA collaboration for FAIR (more than 800 members from 30 countries). In addition, GSI-MML cooperates with the European Space Agency (ESA). During FAIR Phase-0, GSI offers 3 months/year of beam time. The national university partners are funded by the BMBF ErUM framework program, including the research priority program APPA [1]. GSI-MML scientists support users throughout the entire process, including preparation and execution of the beam time as well as data storage and analysis.

2.1 Atomic physics

Head: Prof. Dr. Thomas Stöhlker (HI Jena, FSU Jena & GSI)
Authors: Carsten Brandau, Alexandre Gumberidze, Wolfgang Quint, Michael Lestinsky, Esther Menz (HI-Jena, GSI), Konstantin Mohr (TU-Darmstadt & GSI), Sonja Bernitt, Thomas Stöhlker

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. For this purpose, the storage ring / ion trap complex ESR / CRYRING@ESR / HITRAP (part of the modularized FAIR facility) offers fascinating, worldwide unique possibilities by providing cooled heavy ion beams, for basically all elements (from hydrogen to uranium) in every charge state up to fully ionized uranium. A particular unique selling point of the storage ring/ion trap complex ESR / CRYRING@ESR / HITRAP is that cooled ions can be provided over a wide energy range from rest in the laboratory up to relativistic velocities of approx. 70% speed of light. The combination with the fragment separator (FRS) allows to extend the research spectrum to short-lived nuclides. All together, these unique and highly relevant research op-portunities allow for a rich spectrum of atomic physics experiments, with the main focus on the investigation of quantum dynamics and quantum electrodynamics in extremely strong Coulomb fields as they prevail in the heaviest highly charged ions (close to the Schwinger limit). In addition, atomic physics research at GSI extends to neigh-boring fields such as accelerator physics, materials research, plasma physics, and especially atomic and nuclear as-trophysics. To reach its research goals, particular important activities of the AP division are related to the develop-ment 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). Instru-mentation and detection concepts are permanently under scrutiny and in case adjusted, to enabled optimal use of the above-mentioned research infrastructures.

In 2023, emphasis was given to preparation of various experimental setups for the beam times within the FAIR Phase-0 program in 2024 and 2025. In addition, two beam times have been carried out at the CRYRING@ESR using the ions from the local ion source and injector.

Note, for many of the research activities presented below, the AQF Department has teamed up with the Helmholtz Institute Jena, a research institute of GSI at the campus of the Friedrich-Schiller University of Jena, which in some cases even took the lead (for the annual report of HI-Jena, please check out Annual Reports of the Helmholtz-Institut Jena (hi-jena.de).

Highlights in 2023

Precision tests of quantum electrodynamics in extreme fields

Quantum electrodynamics (QED) describes interactions between light and matter, and is an important corner stone of the Standard Model. Testing it with high precision, especially in the regime of extremely strong electromagnetic fields, is therefore of high importance for fundamental research, e.g. precision tests of the Standard Model, as well as for applications, such as new frequency standards.

Great step forward has been made in regard of benchmarking strong-field QED and state-of-the-art many-body theoretical approaches. Namely, in a precision x-ray spectroscopy measurement at the gas-jet target of the Experimental Storage Ring (ESR), an intra-shell transition in the heaviest two-electron system, i.e. helium-like uranium (U^{90+}) has been measured with a record accuracy of 37-parts-per-million using specially designed Bragg crystal spectrometers [1]. This allows, for the first time in this regime, to disentangle and to test high-order QED effects (one-electron two-loop) as well as two-electron QED contributions (see Figure 5). Moreover, the experimental result can discriminate between various theoretical approaches developed throughout last decades for description of helium-like ions and thus establishes a very important benchmark for theory in the regime of extremely strong electromagnetic fields.

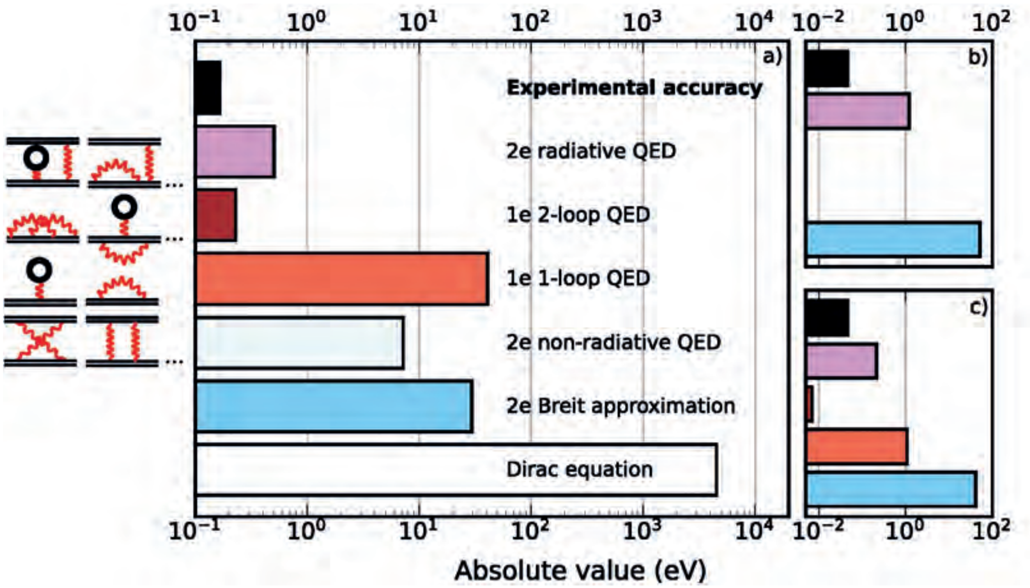


Figure 5. Experimental sensitivity to theoretical contributions. a–c, Theoretical contributions to the $1s_{1/2}\,2p^{3/2}$ $J = 2$ -> $1s_{1/2}\,2s_{1/2}$ $J = 1$ intra-shell transition energy in He-like uranium (a), to He-like and Li-like uranium transition energy difference (b) and to Be-like and Li-like U transition energy difference (c) in comparison with our experimental precision. For (b) and (c), the blue bar includes non-radiative QED contributions. Some of the corresponding Feynman diagrams are also represented. 1e and 2e stand for one-electron and two-electron contributions, respectively.

Furthermore, a significant progress has been achieved with specially developed metallic magnetic microcalorimeters (MMC) which have been deployed for precision spectroscopy at the gas-jet target of the ESR [2,3]. In these measurements, x-ray transitions of hydrogen- and helium-like xenon (Xe^{53+} and Xe^{52+}) as well as of lithium- and beryllium-like uranium ions (U^{89+}, U^{88+}) have been measured with high resolution demonstrating a big potential of these detection systems, in particular regarding the possibility of spectroscopic determination and correction of the relativistic Doppler effect.

In a joint experiment of DESY, GSI and HI-Jena, the Rayleigh scattering of highly-linearly polarized hard x-rays on gold target has been studied at P07 beamline of PETRA III facility [4]. Namely, angular differential cross sections have been measured both in and out of the polarization plane of the incident beam. The obtained results are in agreement with state-of-the-art calculations and may have considerable impact on future experiments regarding a polarization-resolved analysis of Delbrück scattering which represents another interesting venue for exploring effects of the strong-field QED. Here, a very significant progress has been made recently on theory side by accomplishing all-order (in the nuclear binding strength parameter) calculations Delbrück Scattering above the pair-production threshold [5].

FAIR Phase-0: experiments

CRYRING@ESR

Di-electronic recombination (DR) measured for Ne^{3+} ions

Neon is one of the most abundant elements in the universe and emission lines of several of its low charge states can easily be identified in spectroscopic measurements of cold photoionized plasma, like in planetary nebulae. Precise knowledge of – among others - recombination rates are vital for a modelling of charge state distributions in such plasma and dielectronic recombination (DR) is the dominant recombination channel. Therein, the capture of free electron from the continuum resonantly excites a bound electron from the atomic shell of the ion, forming a doubly excited state. Astrophysical modelling codes implement this process largely by relying on theoretical data and only limited experimental data is available for low charge-state ions. Moreover, it is known that the reliability of theoretical calculations is limited at low electron-ion collision energies which have the largest impact on the low-temperature plasma rates.

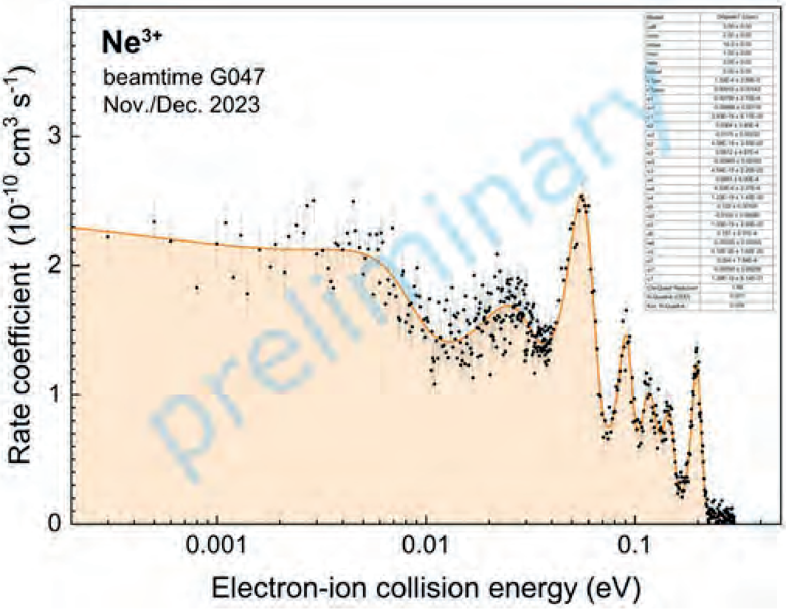


Figure 6. Preliminary experimental data for DR of Ne^{3+} ions measured at the CRYRING@ESR electron cooler.

To address this lack of experiment data, we have started an Astro-DR research program, within which we measured DR in Ne^{3+} at the electron cooler of CRYRING@ESR (G-PAC proposal number G-22-00047). Its lowest-energy Δn=0 DR resonances form an O-like Ne^{2+} ion where the inner active electron is being excited within the L-shell and Δn=0 DR resonances can be found up to electron-ion collision energies E_{cm} of about 23 eV. The experiment at CRYRING@ESR was highly successful in revealing a wealth of resonances for $E_{cm} < 1$ eV, whose positions do not agree with spectra obtained with the AUTOSTRUCTURE code. Detailed data analysis is currently ongoing. Our experimental results are vital for both accurate astrophysical modelling and for refining theory in future. Figure 6 shows the preliminary experimental data fitted with Lorentzian resonance profiles.

Laser spectroscopy of ^{25}Mg^{+} at CRYRING@ESR

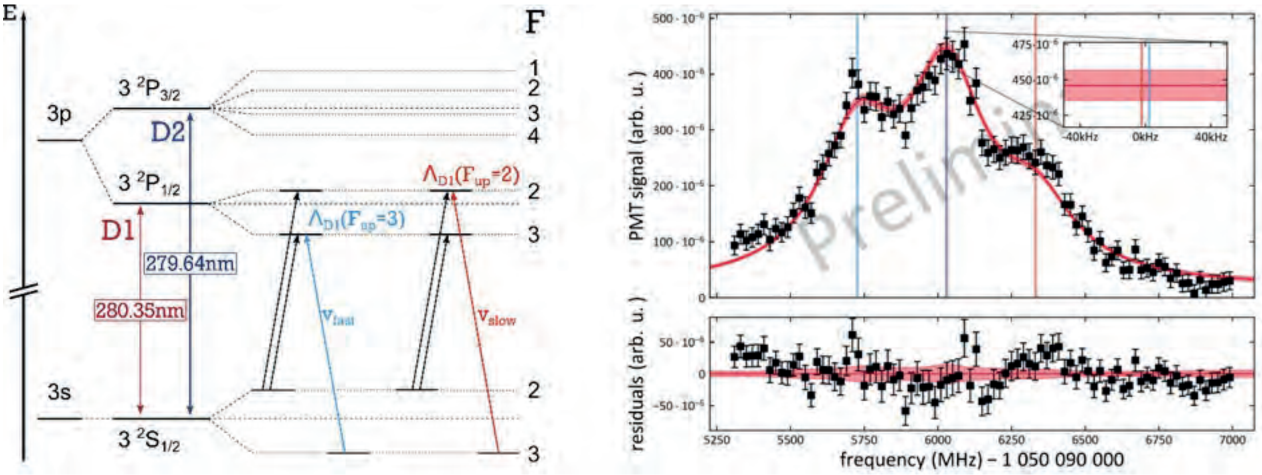


Figure 7. On the left is the level scheme of singly charged ^{25}Mg^{+}, where additional contributions from the fine and hyperfine structure are considered. Within the hyperfine structure two possible Λ-type transitions are indicated. They can be addressed sim-ultaneously for a slow (vslow) and a fast (vfast) velocity class if the Doppler width of the ion ensemble is larger than the splitting of the upper hyperfine levels $2P_{1/2}$ (F=2) and $2P_{1/2}$ (F=3). Therefore, not only two but four transitions are observed, the positions of which are indicated by the colored vertical lines in the spectrum on the right. Since only a few kilohertz separate two of these lines, they overlap in the central peak of the resonance profile. This is shown in the inset of the spectrum. Image: K. Mohr / TUDA, GSI

The laser spectroscopy experiment G-00058 aims to test whether a polarization build-up by optical pumping can be observed at CRYRING@ESR. During the beam time in December 2023, a coasting beam of ^{25}Mg^{+}-ions was targeted by Λ-type optical-optical-double-resonance (OODR) laser spectroscopy. We found that individual hyperfine lines can be resolved (see Figure 7), which demonstrates the high-precision capabilities of the CRYRING@ESR storage ring in combination with its ultra-cold electron cooler. The extracted fine-structure transition frequencies of the spectra are in good agreement with the literature values and consolidate the assumption that the pump laser addresses at least two velocity classes at the same time. Since complicated ion beam dynamics can lead to mixing of velocity classes during the storage time, the ongoing analysis of the data needs to be combined with simulations to disentangle the influence of polarization effects from potentially superimposed dynamic effects to the relative intensities of the individual lines.

SPARC transverse free-electron target

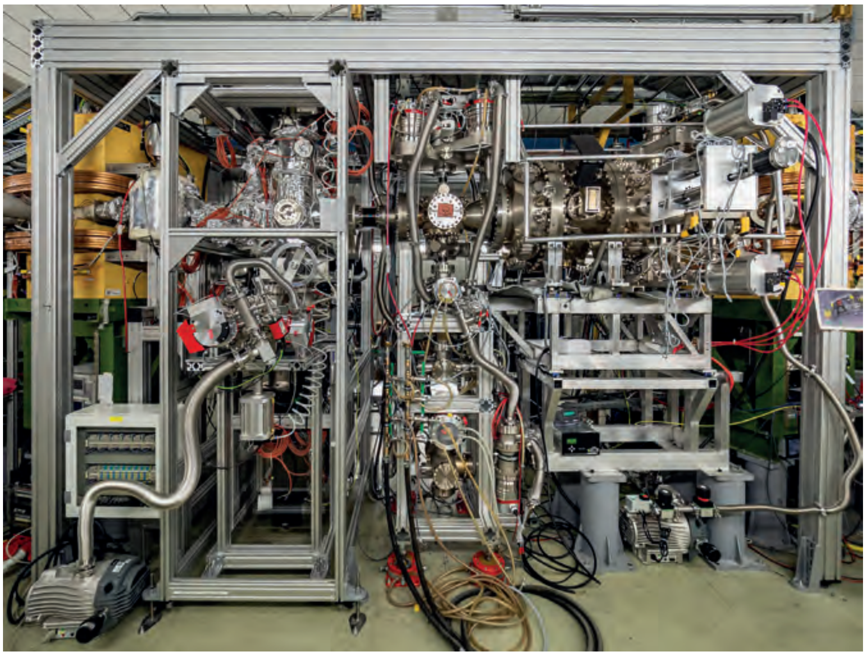


Figure 8. Experimental installations in the CRYRING section YR09. From left to right: electron target, gas-jet-target and the nuclear astrophysics detector array CARME.

In 2023, the gun section of the SPARC transverse free-electron target (Figure 8) was relocated from the laboratories at the Justus-Liebig-University in Giessen to a new set-up space at GSI. Already during reconditioning of the cathode and offline re-commissioning using a limited set of power supplies and electron current of more than 100 mA could be extracted whereby the measured electron current is in excellent agreement with the simulations of the gun. The base vacuum, i.e., with the cathode switched off, of the gun section as well as of the electron target interaction chamber is excellent in the low 10^{-11} mbar region. in summer 2023 the gun section was merged with interaction chamber which was already previously installed into section YR09 of CRYRING. The target control system, dedicated detectors and a corresponding data acquisition are presently being implemented, thus working towards a scheduled first commissioning run at CRYRING with beam from its local injector in spring 2024.

Towards First Experiments at HITRAP

ARTEMIS experiment at HITRAP: Fast-opening cryogenic valve implemented

The ARTEMIS experiment was successfully connected to the HITRAP beamline via a novel fast-opening cryogenic valve (FCV). The FCV isolates the cryogenic environment of the trap with a pressure better than $2.4\times10e^{-16}$ mbar from the room temperature HITRAP low energy electrostatic beamline. It allows injection of heavy, highly charged ions (HCIs) from HITRAP. This is the first example of a valve capable of both cryogenic isolation for long storage of heavy HCIs as well as fast opening times as short as tens of milliseconds. A non-destructive position sensitive di-agnostic detector in the beamline at ARTEMIS serves for continuous monitoring of the injection during experiments. Figure 98 shows a photo of the completed FCV below the ARTEMIS magnet next to a CAD drawing of the interior of the valve.

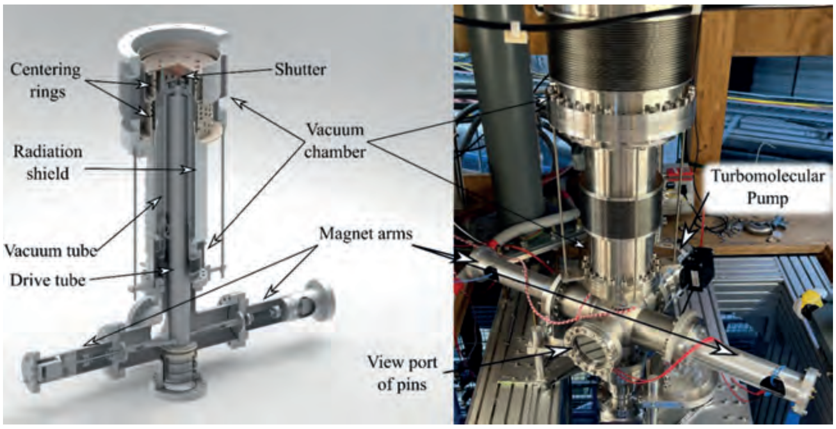
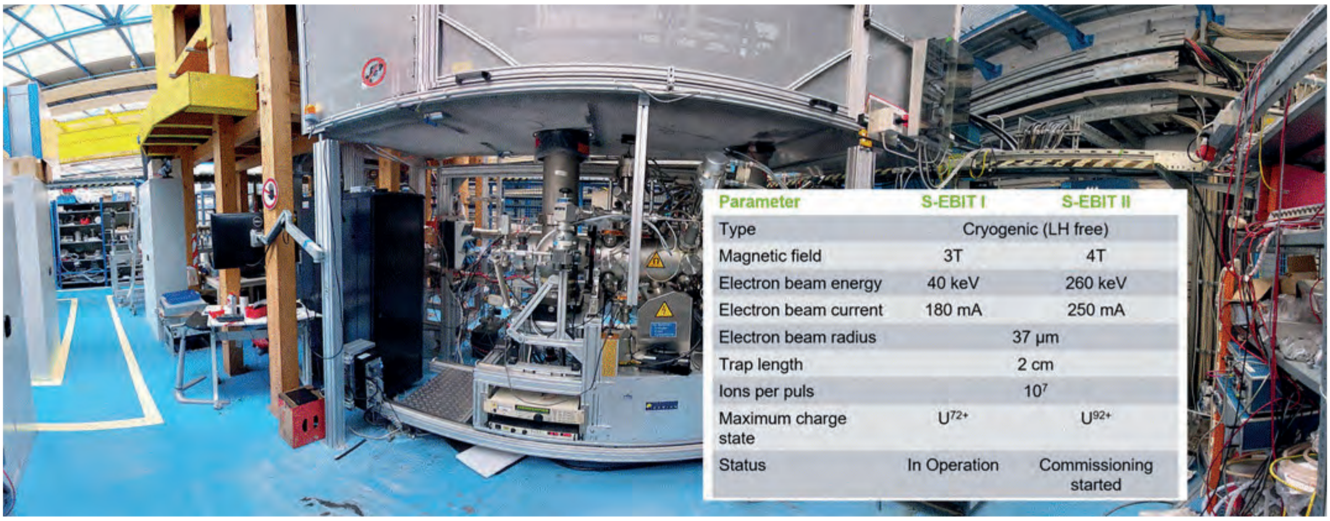


Figure 9. A cutaway rendering of the FCV and a photo as it is installed at ARTEMIS.

New superconducting magnet for SPECTRAP at HITRAP:

The CAD design to adapt the cryogenic Penning trap setup of SPECTRAP at HITRAP to the new superconducting magnet has been completed within a master thesis in close cooperation between GSI/FAIR and University of Uppsala and University of Stockholm.

The Electron Beam Ion Trap (S-EBIT-II)



Parameter	S-EBIT I	S-EBIT II
Type	Cryogenic (LH free)	
Magnetic field	3T	4T
Electron beam energy	40 keV	260 keV
Electron beam current	180 mA	250 mA
Electron beam radius	37 µm	
Trap length	2 cm	
Ions per puls	10^7	
Maximum charge state	U^{72+}	U^{92+}
Status	In Operation	Commissioning started

Figure 10. Photo of the S-EBIT-II facility on the HITRAP platform. The important parameters of both S-EBIT-I and S-EBIT-II are shown as well.

S-EBIT II, an electron beam ion trap located next to the HITRAP beamline and intended as a stand-alone source of highly charged ions (see Figure 109), was made operational for the first time. X-ray spectroscopy was used to confirm the presence of trapped few-electron argon ions. This success was followed up by measurements of x-ray fluorescence induced by dielectronic recombination. These measurements serve to judge and improve machine performance. Some ion optics elements required for injection of ions into the HITRAP beamline have been installed or prepared for installation.

Selected publications of 2023

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- [2] M. O. Herdrich et al, Eur. Phys. J. D 77, 125 (2023).
- [3] M. O. Herdrich et al, Atoms 11, 13 (2023).
- [4] W. Middents et al, Phys. Rev. A 107, 012805 (2023).
- [5] J. Sommerfeldt et al, Phys. Rev. Lett. 131, 061601 (2023).

2.2 Materials research

Head: Prof. Dr. María Eugenia Toimil-Molares (GSI & TU Darmstadt)
Authors: Walter Assmann (LMU), Shankar Dutt (Australian National University, Canberra, Australia), Leon Kirsch (GSI and LMU), Alexander Kiy and Patrick Kluth (Australian National University, Canberra, Australia), Mohan Li (GSI and TU Darmstadt), Eugenia Toimil-Molares (GSI and TU Darmstadt), Christina Trautmann (GSI and TU Darmstadt), Nils Ulrich (GSI and TU Darmstadt), Michael Wagner (GSI)

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

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

To support the interdisciplinary MAT collaboration, which consists of more than 40 groups from Germany and abroad, the Materials Research Department maintains and operates several beamlines with an extensive variety of techniques. The lack of beamtime in 2023 presented a significant challenge for the materials science community and related interdisciplinary fields. The research efforts focused on utilizing and analyzing previously irradiated samples, while important technical developments were also undertaken, including upgrading the control systems of the M-branch and reconstructing the sample preparation and control room of the X0 beamline. During the engineering run in November 2023 with 200 MeV/u U^{73+} ions in cave A, a new adjustable beam collimator was successfully tested. The initially few mm broad beam was collimated down to 200 µm, which minimizes activation of the diamond pressure cells. Additionally, a new irradiation geometry was tested by exposing the miniaturized samples through the so-called gasket (a metal disk with an aperture which acts as sample container and separates the two pressing diamonds). This setup keeps the passage through the diamond anvils free and thus provides access to the sample by Raman spectroscopy. For optimization, various gaskets materials (stainless steel, Re, W, and Ta) were irradiated and their deactivation is currently being evaluated in cooperation with the safety and radiation protection department.

Highlights in 2023

Ion tracks and conical nanopores in amorphous SiO_2 membranes

Nanopore membranes are a versatile platform for a wide range of applications ranging from medical sensing to filtration and clean energy generation. To attain high-flux rectifying ionic flow it is required to produce channels exhibiting asymmetric surface charge distributions. Ion-track nanotechnology provides a versatile platform for the synthesis of solid state nanopores with tailored shape and size. The etching process to convert ion tracks into open channels has been extensively developed for a range of polymers, yet it remains relatively underexplored for silicon-based materials. The group of Prof. P. Kluth at the Australian National University investigated ion tracks and the formation of conical nanopores in amorphous SiO2, a material which is compatible with silicon microelectronic manufacturing processes.

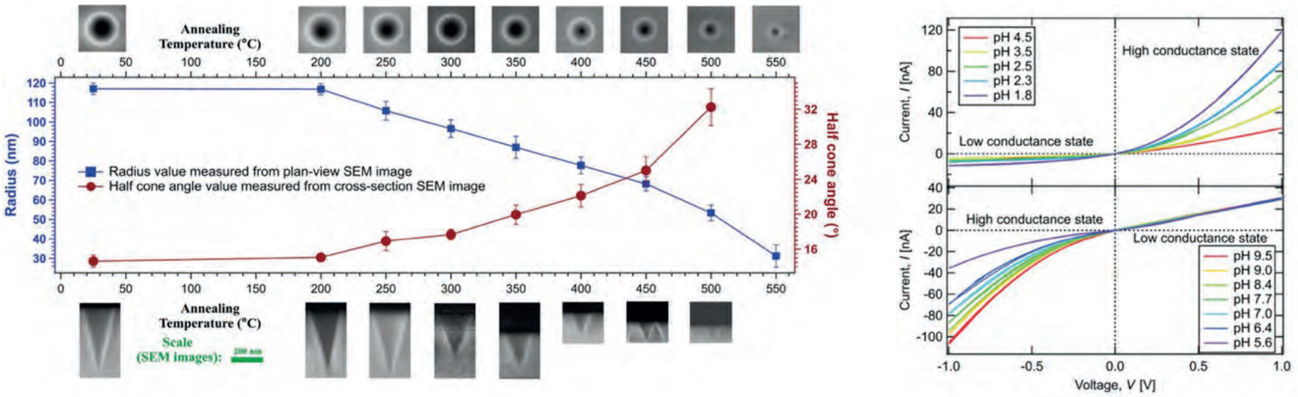

Figure 11. (Left) Radius (blue squares) and half cone angle (red circles) of conical etch pits (10 min in 3 % HF) in ion-irradiated amorphous SiO_2 as a function of the annealing temperature (30 min). Microscopy images of top-views (top) and cross-sections (bottom) of the etch pits [1]. (Right) I-V curves measured in 100 mM KCl for different acidic and basic conditions ranging from pH 1.8 to pH 9.5 [2].

Thin SiO_2 films were irradiated at the UNILAC with 1-2 GeV Au ions and subsequently etched in 3% hydrofluoric acid. The resulting channels are conical and have a half-cone opening angle of about 15°. The pore size and cone angle can be tailored by annealing the irradiated SiO_2 samples. Combined electron microscopy and small angle X-ray scattering experiments at the ANSTO Australian Synchrotron [1] reveal that track annealing above 250° C has an impact on the track etch rate and changes as a function of depth. With increasing annealing temperatures, the size of the etch pits decreases and the half-cone angle increases (Figure 11 left). The conductometric properties of track-etched conical nanopores in amorphous SiO2 membranes were characterized by recording I-V curves (Figure 11 right). Variations in pH alter the surface charge of the nanopore, consequently affecting ion flow and rectification [2]. These exciting results address some of the challenges that contemporary polymer nanopore systems face and offer a promising alternative platform for nanopore and membrane applications.

Large surface area nanowire networks as catalysts for CO_2 reduction and methanol oxidation

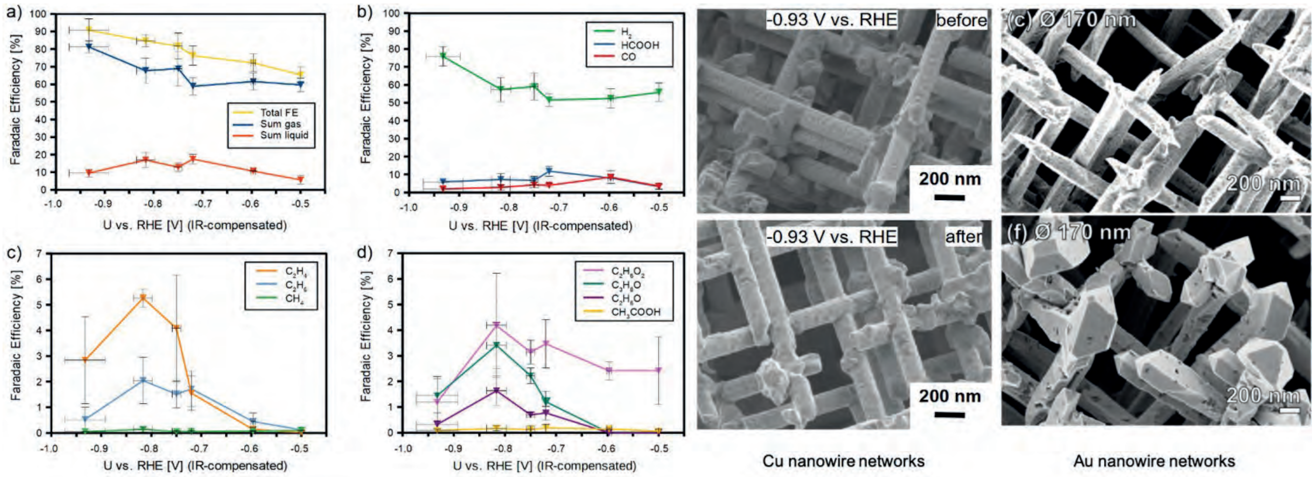

Figure 12. (Left) Faradaic efficiencies (FE) for CO_2 reduction products at Cu-nanowire networks as a function of the IR-compensated potential. (a) in total and separately for the gas- and liquid-phase products; (b) for H_2, HCOOH and CO formation; (c) for carbohydrates C_2H_4 (ethylene), C_2H_6 (ethane) and CH_4 (methane) and (d) for alcohols C_2H_6O (ethanol), C_3H_8O (n-propanol), $C_2H_6O_2$ (ethylene glycol) and CH_3COOH (acetic acid). (Right) SEM images of Cu nanowire networks before and after CO_2 reduction at a potential of -0.93 V vs. RHE, as well as of Au nanowire networks before and after 200 CV cycles of methanol oxidation reaction. Images adapted from [3] and [4].

Developing tailored functional membranes and nanostructured electrodes is relevant for environmental and energy applications such as more efficient separation processes, sensing harmful elements in water or catalysis. Tailored isoporous membranes were produced by irradiating polymer foils with GeV ions under several incident angles in consecutive steps. Chemical etching converts the ion tracks into open channels. Nanochannel density, diameter, and geometry are adjusted by the irradiation and etching conditions, respectively. Subsequent electrodeposition in the nanochannel network results in a mechanically stable three-dimensional nanowire ensembles. The 3D nanowire networks exhibit an electrochemically active surface area that is up to 300 times larger than their planar counterparts, making them extremely interesting for catalytic applications. As detailed in [3], we tested copper nanowire networks as a catalyst for the electrochemical CO_2 reduction toward hydrocarbons and alcohols in an aqueous electrolyte. Varying wire length, diameter and nanowire number density, the specific surface area was adjusted to values between 70 cm^2 and 300 cm^2 per cm^2 geometrical sample area. The conversion efficiency and selectivity of CO_2 reduction toward liquid- and gas-phase products was monitored as a function of the applied potential (Figure 12 left). We characterized the nanowire networks by scanning and transmission electron microscopy and X-ray diffraction before and after the CO2 reduction reaction, evidencing their stability during CO_2 reduction in a potential region between −0.5 V and −0.93 V versus RHE (Figure 12 right). We also tested the catalytic performance of a highly interconnected Au nanowire network with diameters between 80 and 170 nm [4]. All networks showed a very stable performance during 200 cyclic voltammetry (CV) cycles of methanol oxidation reactions, with the peak current density reaching up to 200 times higher than that of a flat reference electrode, with only a 5% drop in the peak current density. The Au nanowire networks proved to be excellent model systems for investigating the performance of porous catalysts and very promising nanosystems for application in direct alcohol fuel cell catalysts.

Experimental evidence of a size-dependent sign change of the Seebeck coefficient of Bi nanowire arrays

The electrical transport in bismuth nanowires is strongly influenced by both sample geometry and crystallinity. Compared to bulk bismuth, the electrical transport in nanowires is dominated by finite- and quantum-size effects and influenced by surface states, which gain increasing relevance as the surface-to-volume ratio increases, meaning as the wire diameter decreases. By combining ion-track nanotechnology and electrodeposition, we synthesized bismuth nanowires with tailored diameter and crystallinity. These nanowire arrays serve as excellent model systems for studying the interplay of the different transport phenomena. Seebeck coefficient and relative electrical resistance were measured as a function of temperature for parallel bismuth nanowire arrays with diameters between 40 and 400 nm synthesized by pulsed electroplating in polycarbonate track-etched membranes [5]. Both the electrical resistance and Seebeck coefficient exhibit a non-monotonic temperature dependence with the sign of the Seebeck coefficient changing from negative to positive with decreasing temperature. The observed behavior is size-dependent and is attributed to limitations in the mean free path of the charge carriers within the nanowires. The size-dependent Seebeck coefficient and particularly the size-dependent sign change opens a promising avenue for the development of single-material thermocouples with p- and n-legs made from nanowires with different diameters.

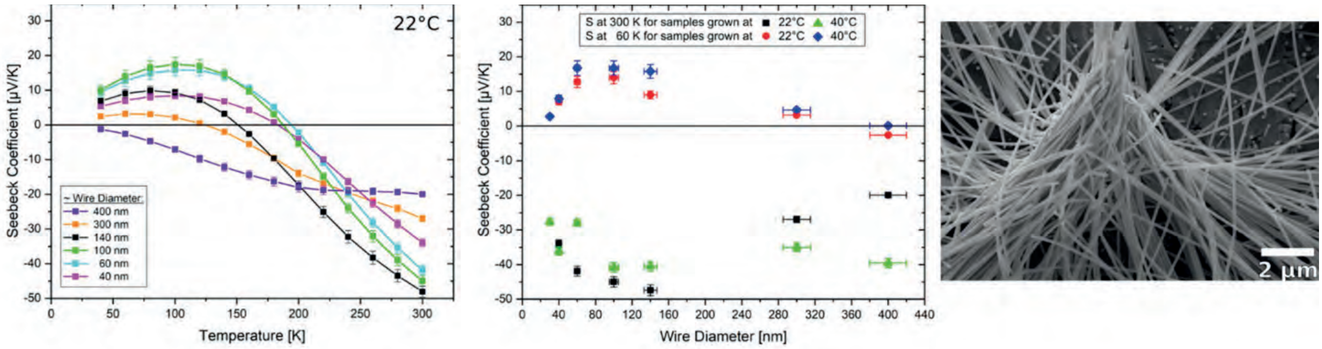

Figure 13. (Left) Seebeck coefficient of Bi nanowire arrays embedded in a polycarbonate template as a function of temperature. (Center) Seebeck coefficient S as a function of nanowire diameter at 300 K (black squares and green triangles) and at 60 K (red circles and blue diamonds). (Right) SEM image of an array of Bi nanowires after dissolution of the polymer template.

This work is part of the activities of the Innovation Pool Project MaDQuant (Materials Dynamics for Future Quantum Technology), which aims at identifying relevant quantum materials to achieve a microscopic understanding of the materials and excitations, to investigate dynamic states and their coupling to the environment, and to identify possible technological applications.

Ionoacoustic monitoring of relativistic heavy ion beams

Experiments at SIS18 with Xe, Pb and U ions of energies between 200 MeV/u and 1 GeV/u have demonstrated that the ionoacoustic technique provides an effective method for analyzing beam properties such as energy and intensity. Together with the team of the Ludwig-Maximilians-Universität München, we investigated transient acoustic waves generated when µs-long pulses of relativistic ions enter a water container equipped with a piezoelectric detector (transducer). The acoustic signal primarily originates from the region where the ions experience maximum energy loss (Bragg peak) close to the point where the ions come to a stop (Figure 14 left). By analyzing the time delay between the primary and reflected waves, we can obtain information about the range of the ion pulse with an accuracy of 1 %. This range data, when combined with a simulation code such as FLUKA, allows us to determine the ion energy [6]. The acoustic signal compared with a reference signal from a secondary electron monitor (SEETRAM has a linear correlation (Figure 14 right) across an extensive range of at least 10^4 to 10^9 particles per spill. Additionally, the ionoacoustic technique permits energy loss measurements of relativistic ions in a specific material by inserting a target of known thickness into the beam and determine the resulting ion-range reduction in water. The advantage of the ionoacoustic technique lies in its rather simple experimental setup, resilience to radiation, wide dynamic range, and the availability of real-time information through individual pulses.

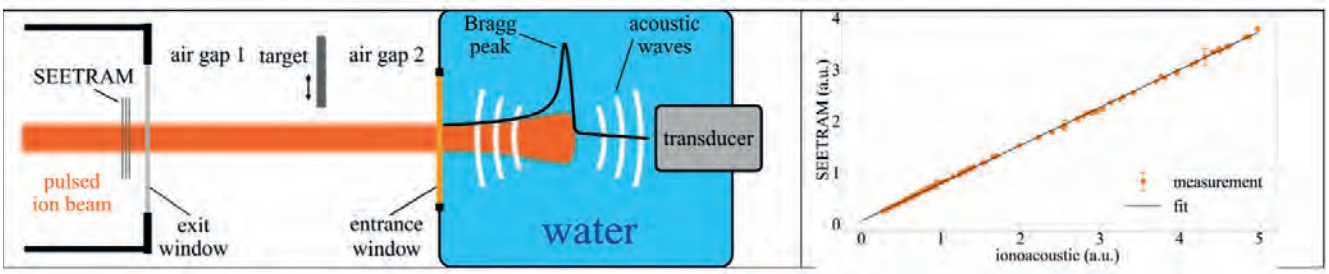

Figure 14. (Left) Schematic of the ionoacoustic setup for relativistic ion beams. The ion pulse exits the beamline vacuum, travels through the air gap and enters the water container. Energy deposition from the ions initiates an ionoacoustic wave at the Bragg peak shortly before the ions stop. The primary and reflected acoustic signal is registered by the ultrasonic transducer mounted on beam axis. The time delay between the two signals yields information on the ion penetration depth. A remote-controlled stage in front of the water container allows insertion of targets for energy loss measurements. (Right) Comparison between the ion pulse signal of the piezoelectric transducer and a SEETRAM reference signal.

Outlook for 2024

Following the ‘Call for Proposals’ for beamtime in 2024 and 2025, the MAT-PAC evaluated the scientific excellence and recommended 19 A-rated proposals as high priority experiments. For the next beamtime block in early 2024, FAIR Phase-0 activities will continue at all MAT-operated beamlines. During the second half of the year, the heavy ion microprobe will be upgraded within a HI-ACTS project to provide remote control and a more user friendly operation in particular for testing the radiation hardness of electronic components. 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. Two new third-party funding projects, KATH-DRAHT and TRANSIEVES will start in 2024. The research objectives of these two initiatives deal with the development of 3D nanowire assemblies to enhance the thermal transport in fuel cell cathodes and with the investigation of AC-controlled ionic transport properties of tailored nanopores, respectively.

Selected publications of 2023

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2.3 Plasma physics

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

The Plasma Physics Department operates several experimental facilities at GSI for experiments in the field of HED science. At the target area Z6 in the experimental hall of UNILAC, a unique combination of ion pulses from the linear accelerator and laser pulses from the high-energy laser facility PHELIX allows precise measurements of the ion stopping power in laser-generated hot plasmas as well as to investigate advantages of combining laser accelerated ions and conventional accelerator structures. Stand-alone laser experiments can be performed in the PHELIX laser hall, where relativistic intensities in high-energy picosecond pulses are available for experiments on relativistic laser-matter interaction, laser-particle acceleration and the generation of intense secondary sources. Finally, at the high-temperature experimental station HHT at 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 duration, allowing macroscopic samples to be volumetrically heated to extreme conditions. With the recently completed high-energy laser beamline from the PHELIX building to the HHT cave, experiments combining this novel way to create extreme states of matter with diagnostic techniques based on laser-driven secondary sources can be carried out.

Within the current FAIR Phase-0, these GSI facilities are also essential for the FAIR-relevant research program of the international FAIR collaboration HED@FAIR, which aims at exploiting the unique ion beam parameters that will be available in the APPA cave for HED science experiments. The plasma physics department as the GSI-based part of HED@FAIR coordinates the on-site activities preparing the technical and experimental infrastructure and diagnostic setups.

Operation report of the plasma physics user facility

The PHELIX laser system, operated since 2008 by the GSI plasma physics department, is currently delivering the most energetic laser pulses within Germany. Like the GSI accelerator complex, PHELIX is operated as a user facility, i.e. open to the international scientific community, with beamtime access granted by an external program advisory committee. Similar to 2022, in the past year about 43% of the time was used for beamtimes and preparation, while 42% were dedicated to maintenance and development. A total of 9 experiments were performed in 2023 using the PHELIX laser, covering a diverse range of topics including laser ion acceleration, implantation and detector development, x-ray phase contrast imaging, gamma and neutron source development, nuclear photonics and relativistic laser-matter interaction. While most of the experiments were “laser-only” experiments, conducted in PHELIX Target Area, one beamtime used high-energy laser pulses at the HHT-cave, optimizing laser-driven x-ray sources in preparation for the 2024 beamtime block, for which another set of combined laser/accelerator experiments are foreseen. At the Z6 target area, this year no beamtimes were served, due to major upgrade activities on the nhelix laser system there. The evaluation of questionnaires handed out to the users at the end of their beamtime showed good feedback about PHELIX operation. A total of 474 shots on target were recorded in the PHELIX shot database, with a shot success rate of 98.5%. This underlines the high level of reliability of the system in its sixteenth year of user operation.

The operation of the PHELIX facility is also to be seen in combination with a constant effort to improve and develop its experimental capabilities. In experiments with laser pulses at relativistic intensities, small amounts of laser light preceding the main pulse can significantly alter the conditions at which the laser interacts with the target. To gain a better understanding of the fundamental mechanisms, and for a meaningful comparison of experimental data with simulations of the relativistic laser matter interaction, accurate knowledge of the preplasma conditions is paramount. In order to enable measurements of the preplasma formed, we have developed a synchronized off-harmonic probe laser (SEPPL, [1]), seeded by a part of PHELIX itself, with a highly variable pulse duration, ranging over more than three orders of magnitude from 3.5 ps up to 10 ns at pulse energies in the mJ range. The frequency doubled probe laser enables different diagnostic methods for experimental campaigns at PHELIX, such as side-viewed interferometry or streaked shadowgraphy, with a ratio between signal and self-emission that is larger than 110. Additionally, the delay to the main pulse can be tuned by approximately 200 ns while maintaining an RMS jitter between probe and main pulse below 2.5 ps. Figure 15 shows exemplary measurements of the plasma expansion using short-pulse interferometry and streaked shadowgraphy of a 20 μm thick gold target with an artificial prepulse.

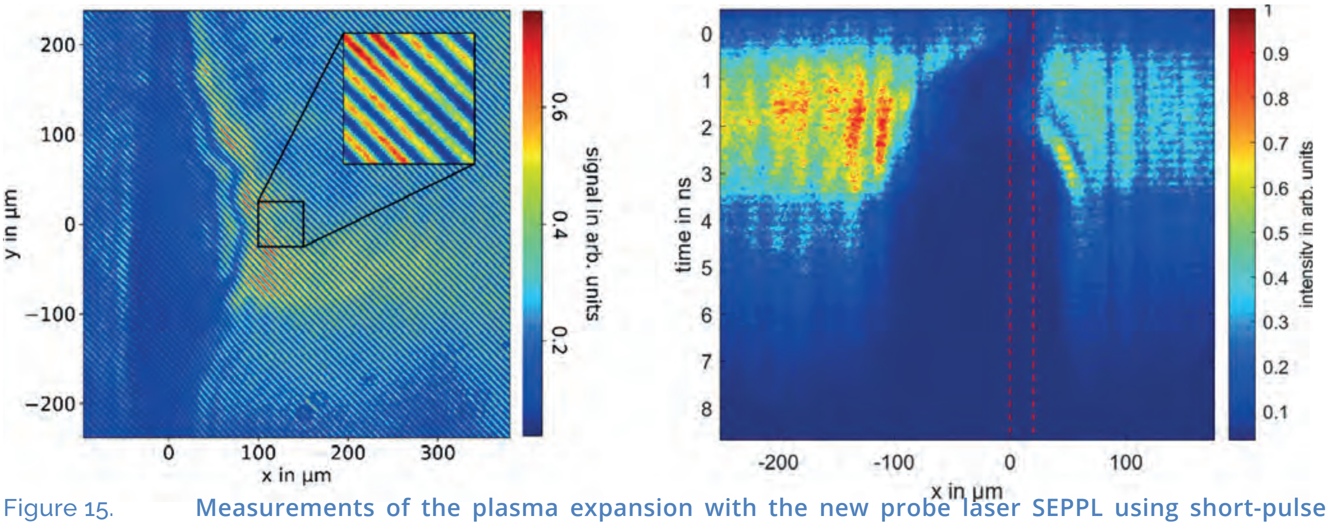

Figure 15. Measurements of the plasma expansion with the new probe laser SEPPL using short-pulse interferometry (left) and streaked shadowgraphy (right) of a 20 μm thick gold target with an artificial prepulse.

Also in 2023, the upgrade project of the nhelix-laser at the Z6 experimental area was completed. This complete rebuild of the laser system uses two new Nd:glass rod amplifiers (19 and 45 mm diameter), and finally a 300 mm aperture slab amplifier (the same modules as used in the PHELIX main amplifier chain) in a multi-pass configuration. The new system has successfully produced laser pulses with up to 65 J of pulse energy at the second harmonic. This significant upgrade in pulse energy now allows generation of hot laser-driven plasmas using the nhelix laser alone. In combination with PHELIX, this will enable the use of very intense, sub-ns laser-accelerated ion bunches for stopping power measurements in laser-driven plasmas, which is expected to yield increased accuracy for benchmarking theoretical predictions.

Highlights in 2023

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 laser performance and beam quality, and to expand diagnostic capabilities. As an example, over the last decade, the laser-plasma community developed an increasing interest in using laser beams with Orbital Angular Momentum (OAM), which exhibit a ring-like structure in the focal plane. These beams are notoriously hard to optimize as the ring structure is extremely sensitive to angular phase aberrations compared to regular beams without OAM. In the last year, the PHELIX crew has developed a novel technique for the direct optimization of these beams, called ZEHBRO (Zernike-coefficient Extraction via Helical Beam Reconstruction for Optimization) in the far field [2]. Addressing the limitations of traditional beam optimization methods, ZEHBRO offers a much finer control by directly observing and reconstructing the focal ring of these “donut-like” beam, enabling uniform focal rings in high-intensity laser applications. Proven effective at the 100 TW beamline of the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility, ZEHBRO marks a significant improvement towards laser-plasma experiments with OAM beams, including directed laser particle acceleration, overcoming previous challenges associated with ring distortions inside experimental chambers.

Strong electromagnetic pulses (EMPs), generated in intense laser-matter interactions, can be guided by the target geometry, specifically through conductive connections to the ground. In an experiment at the PHELIX laser, an international group led by the Universities of Bordeaux and Darmstadt could for the first time characterize simultaneously discharge current and return current driven by relativistic laser pulses interacting with solid density targets [3]. Using the dual-beam mode of PHELIX, an experimental characterization by time- and space-resolved proton deflectometry (see Figure 16) of guided electromagnetic discharge pulses could be realized in a pump-probe scheme. This allowed observation of EMPs, generated by 0.5 ps, 50 J, 10^{19} W/cm^2 laser pulses, with electric-field amplitudes of multiple GV/m with durations of tens of ps, from currents in the kA-range. Experimental results are supported by analytical modeling and high-resolution numerical particle-in-cell simulations, unraveling the likely presence of a surface plasma, in which parameters define the discharge pulse dispersion in the non-linear propagation regime.

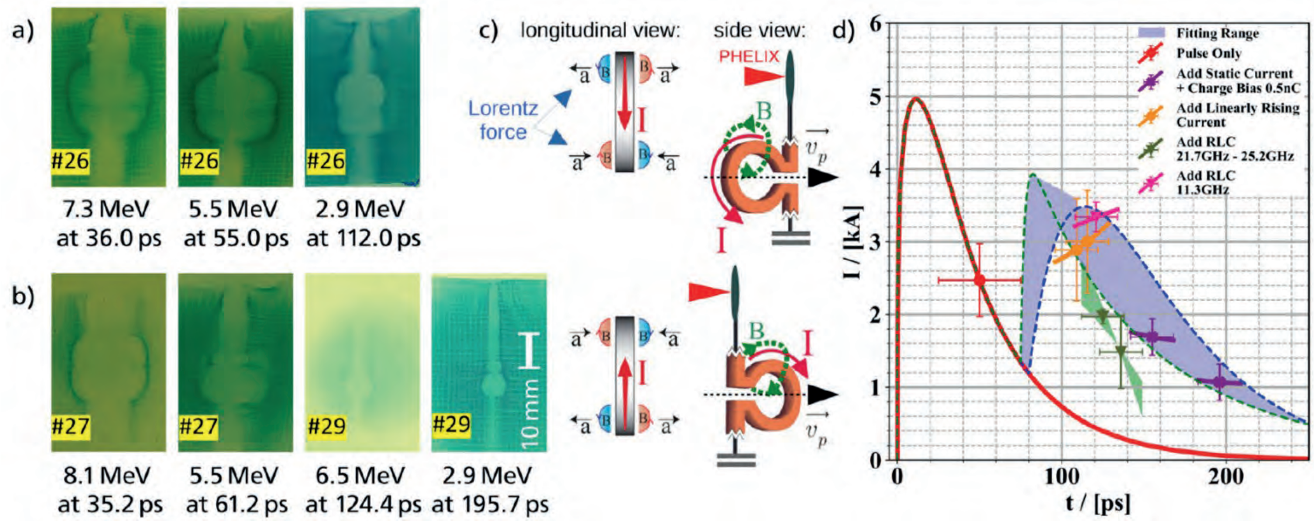

Figure 16. Proton deflectometry images a), b) of the ultra-intense laser-driven fields around a coil target c), and d) comparison to modeling of the target charging and return current EMP.

In 2023, the 10-M€-large GSI-coordinated THRILL project within the Horizon Europe program, has commenced. This project will address technology bottlenecks for high-energy high repetition rate lasers with partners in France, Czech Republic, Germany and Belgium. An end-user workshop was organized, with presentations of physics being investigated at currently available facilities (XFEL infrastructures, high-power lasers, heavy-ion beam). Future research directions and limitations by currently available laser parameters were discussed. The goal was to formulate specifications for the next generation of high-energy lasers to be developed for research in combination with EuXFEL and FAIR.

FAIR Phase-0: Experiments at the HHT-cave

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.

The PRIOR-II facility at GSI, designed for imaging fast ns-scale experiments with up to 4.5 GeV protons from the SIS18 synchrotron, currently undergoes a transition to enable multiple experiments on shock compressed matter at extreme densities and to serve as a new user facility to the HED community. First experiments to be conducted will include the characterization of new functional materials suitable for use as first contact barriers in magnetic confinement fusion reactors as well as the study of shock compaction as a new approach to larger-scale high-pressure material synthesis.

In order to prepare the facility for the challenges of ultra-fast dynamic experiments starting in 2026, an extensive measurement campaign was carried out during the 2023 engineering run to characterize the 4H4 extraction scheme using a new ultra-fast detector setup based on an array of gated intensified cameras and new fast and bright tiled GAGG(Ce) scintillation screens. The machine performance evaluation and subsequent improvements are crucial to ensure the required sub-percent accuracy of the dynamic areal density reconstruction of the target investigated which is a key parameter for EOS physics calculations.

Furthermore, together with guest scientists from the Los Alamos National Laboratory (LANL), the feasibility of imaging using heavier ions (up to 975MeV/u 12C^{6+} and up to 1.5GeV/u 14N^{7+}) was investigated resulting in the world's first FLASH heavy-ion radiographies. The investigation was performed mainly due to the low availability of protons at GSI, however, despite an expected decrease in spatial resolution performance due to increased energy loss straggling for heavier projectiles, first results also showed an increased areal density contrast compared to proton imaging. This can be explained by the simple fact that due to the dependence of the image contrast on elastic scattering, heavier and larger projectiles will exhibit larger scattering angles due to a larger scattering cross-section and are therefore more likely to be sorted out in the angular collimation stage of the imaging setup. This data is still being analyzed by GSI and LANL to establish a decision matrix based on key parameters of future HED experiments for the choice of the ion species for imaging.

Figure 17. Carbon radiography of a small mechanical wristwatch captured with PRIOR-II using 975MeV/u $^{12}C^{6+}$ beams at the HHT experimental area.

In close collaboration with the biophysics department of GSI, further medical application scenarios of this imaging technique were also evaluated using 300MeV/u 12C^{6+} and novel 225MeV/u 4He^{1+}/12C^{3+} mixed-ion-species beams. For the latter, two different ion species, Helium and Carbon, with equal charge to mass ratio were accelerated and extracted simultaneously from the SIS18 synchrotron. This allowed the demonstration of a simultaneous FLASH tumor treatment and in-vivo position verification scenario where the carbon portion of the beam (~80%) was stopped inside a phantom and the exiting Helium portion (~20%) was used to image a fine structure situated at the Bragg-peak position of the Carbon beam inside the phantom.

For experiments using heavy-ions from the SIS18 synchrotron, the high-energy laser beamline from PHELIX to the HHT-cave allows for experiments combining volumetric heating by the heavy-ion pulses with laser-driven x-ray sources for diagnostics. In the 2024 beamtime block, it is foreseen to perform for the first time extended x-ray absorption spectroscopy (EXAFS) to characterize samples heated by the heavy-ion beam. In preparation for this campaign, this year a beamtime using the PHELIX laser at HHT was dedicated to the development and optimization of this diagnostic scheme. We have tested a new approach to realize a broadband x-ray spectrum, based on the enhancement of continuum emission by radiative recombination, recently demonstrated at the Lawrence Livermore National Laboratory. Together with a newly developed dual-channel crystal spectrometer, highly resolved absorption spectra around the aluminium K-edge could be obtained, already in an experimental geometry that is suitable for heavy-ion heating in future experiments. This preparatory work is thus extremely important to ensure the success of the combined experiments by the HED@FAIR collaboration starting in 2024.

Together with the accelerator department, in the 2023 engineering run we have explored for the first time the transport and focusing of U^{28+}-ions in the HHT-cave. Foreseen for achieving the highest ion numbers in the future SIS100 synchrotron due to the higher space charge limit, up to 3x10^{10} ions could be extracted from the SIS18 and focused in the HHT target chamber. While focusing these higher rigidity beams to mm spot-sizes is not possible with the normal-conducting magnets at HHT, this will still allow for first ion-driven cylindrical compression experiments. New calculations of such compression experiments have shown the possibility to reach conditions where carbon samples undergo transformation to the diamond phase [4].

Outlook for 2024

In 2024, 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 2023

- [1] J. Hornung et al., Synchronized off-harmonic probe laser with highly variable pulse duration for laser–plasma interaction experiments. High Power Laser Science and Engineering.12:e10 (2024), doi:10.1017/hpl.2023.93
- [2] J. B. Ohland et al., Zernike-coefficient extraction via helical beam reconstruction for optimization (ZEHBRO) in the far field. High Power Laser Science and Engineering. 11:e86 (2023), doi:10.1017/hpl.2023.63
- [3] M. Ehret et al., Guided electromagnetic discharge pulses driven by short intense laser pulses: Characterization and modeling, Physics of plasmas 30, 013105 (2023), doi:10.1063/5.0124011
- [4] N. A. Tahir et al., Production of diamond using intense heavy ion beams at the FAIR facility and application to planetary physics, Scientific reports 13(1), 1459 (2023), doi:10.1038/s41598-023-28709-7

2.4 Biophysics

Head: Prof. Marco Durante (TU 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 currently 83 members with background in physics, biology, chemistry, and engineering. The Department is organized in 9 groups, 4 about physics and 5 about biology and has pioneered heavy ion therapy in Europe. In fact, in 2023 we celebrated the 25th anniversary of the start of C-ion therapy at GSI. The first patient was indeed treated in August 1998 with C-ions accelerated at the SIS18 in the pilot therapy project led by Prof. Dr. Gerhard Kraft, at that time head of the Biophysics Department. Unfortunately, Prof. Kraft passed away on March 18, 2023. He was 81 years old and is survived by his wife Wilma, for many years group leader in our Department, and 3 sons, two of them being successful physicists working in research institutes in Germany. A special memorial event to remember the legacy of Dr. Gerhard Kraft was organized at GSI on November 20, 2023. The even had a very large attendance from GSI employees as well as external guests, a memorial lecture from Prof. Jürgen Debus (University of Heidelberg), several memories from the attendants, and finally the Christoph Schmelzer award ceremony.

International Biophysics Collaboration at FAIR

The Biophysics Department is part of the APPA pillar at FAIR. The International Biophysics Collaboration (IBC; www.gsi.de/bio-coll) is a large network of accelerator facilities in operation or under construction with scientific programs in biomedical applications. The delay in the construction of the APPA cave (postponed to 2030) has been discussed within the collaboration and together with the Material Research Collaboration (BIOMAT). We decided to build simple setups to exploit the FAIR (SIS100) beam already from day-1, both at the S-FRS station and at the CBM cave. The initiative was approved by the JSC and the TDR for the setups are currently under evaluation at the ECE.

ESA-FAIR co-operation

In the framework of the ES-FAIR MoU, a new Announcement of Opportunity for Investigations of Biological and Physical Effects of space Radiation (AO-IBPER) has been issued in 2023. The Investigators Working Group Meeting was held at GSI on 13.4.2023 with the participation of the PI of projects selected by the program. Eight proposals have been selected, 4 in biology, 3 in physics and 1 in chemistry. PI are from Germany, Belgium, Czech Republic, UK, France and Italy. They have to share a total of 20 shifts at SIS18 in 2024-25. Moreover, we organized the 3rd 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.

Awards

- Several members of the Biophysics Department received awards in 2023.
- Dr. Francesca Luoni got the award for the best doctoral thesis in physics in 2022 at the Technische Universität Darmstadt.
- Dr. Lennart Volz received the Otto Haxel Award for the best Ph.D. thesis in physics at the Universities of Göttingen, Heidelberg and at KIT.
- Annika Hinrichs and Anastasiia Quarz received the Giersch Excellent Award 2023 from the HGSHire Graduate School for their outstanding scientific work during their Ph.D.
- Prof. Marco Durante got the Henry S. Kaplan award of the International Association for Radiation Research (IARR). The award, which is presented every four years at the International Congress of Radiation Research (ICRR), honors outstanding contributions to the field of radiation research. Established in 1987, this award was received for the first time by a researcher working in Germany during the ICRR meeting in Montreal, August 2023.
- Prof. Uli Weber, head of the Particle Therapy Physics group in our Department, has been called as Professor at the Technische Universität Mittelhessen (THM) in Gießen.

Grants

- The HEARTS project has been funded in the EU Horizon Europe program with 3 M€, about 1/3 to GSI. The project, led by CERN, aims at improving accelerator facilities able to study single event effects in space microelectronics using very high energy heavy ions. The project is implemented at GSI by the group of Space Radiation Physics led by Dr. Christoph Schuy.
- The project COMIX, led by CNAO, is an experiment on the sequence of X-ray radiotherapy and C-ions. Whilst in clinical settings C-ions are generally used as a boost at the end of the treatment, we will study with our GSI beam whether I tis more effective to anticipate the boost before the X-ray treatment. The project wasfunded with 350k€ by the Italian Ministry of Foreign Affairs.
- The project ENDORSE on combination of heavy ion therapy and immunotherapy has been funded by BMBF with 1.6 M€, about ½ to GSI. PI of the entire project is Dr. Claudia Fournier, head of the Immune System radiobiology group in our Department.
- Prof. Christian Graeff, deputy Director of the Biophysics Department, got the prestigious ERC Consolidator Grant to implement the combination of C- and He-ions for simultaneous cancer treatment and online imaging. The project, called PROMISE, will be run in close collaboration with the Accelerator Department and received 2 M€ funding.

Highlights in 2023

This year was exceptionally productive for the Biophysics Department, with 35 peer-reviewed papers in the repository. A few highlights are provided below.

Radiotherapy in upright position

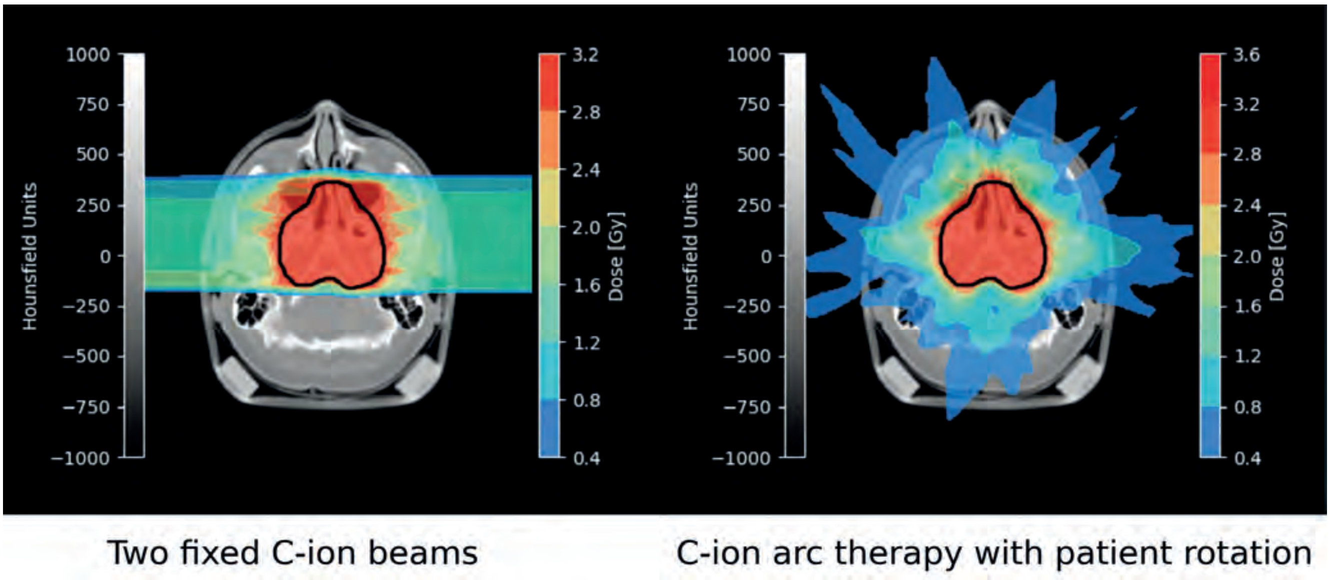

Figure 18. Treatment plan with heavy ions using two opposite field (left) or arc therapy (right). Images courtesy of Dr. Lennart Volz, reproduced under CC-BY 3.0 license. Treatment plan with heavy ions using two opposite field (left) or arc therapy (right). Images courtesy of Dr. Lennart Volz, reproduced under CC-BY 3.0 license.

In collaboration with several academic and industrial partners, we are working on a patient positioning system that allows cancer patients to receive radiotherapy whilst sitting upright – in contrast to having to lie on their back – a position that should reduce organ movement during treatment and may also be more comfortable for the patient. For heavy ion therapy, this system would allow to eliminate the large and expensive rotating gantries thus making heavy ion therapy more affordable [1]. In fact, it will be possible to rotate the chair rather than the beam, thus implementing arc therapy with heavy ions at a low cost (Figure 18).

BARB

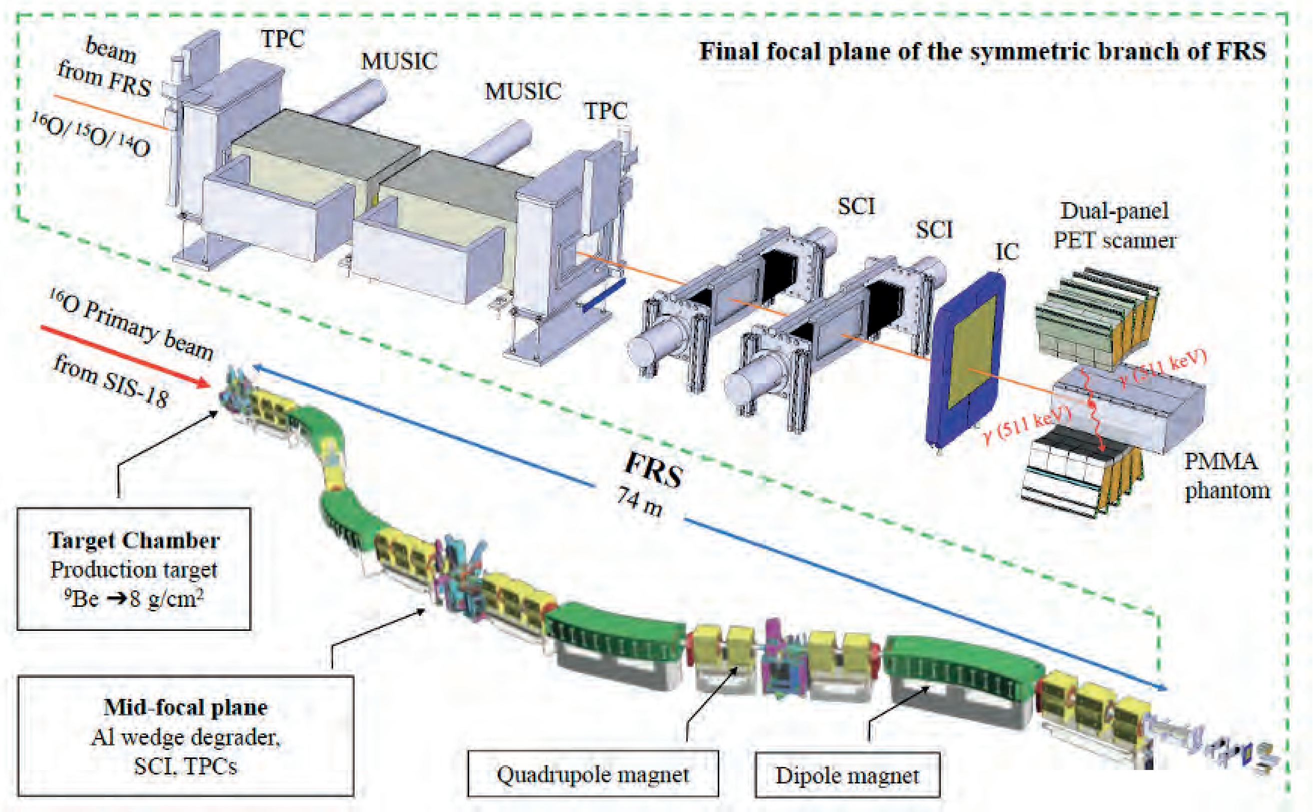

Figure 19. Schematic view of the FRS and a detailed view (inset in dashed line) of the experimental setup at the final focal plane of the symmetric branch of the FRS used for the BARB experiment. Image from ref. [3], reproduced under CC-BY 3.0 license.

The ERC Advanced Grant "Biomedical Application of Radioactive ion Beams" (BARB; www.gsi.de/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), with the external collaboration of LMU in Munich for the construction of the PET detector. Results of PET imaging of radioactive isotopes of carbon [2] and oxygen (Figure 20) [3] have been published this year.

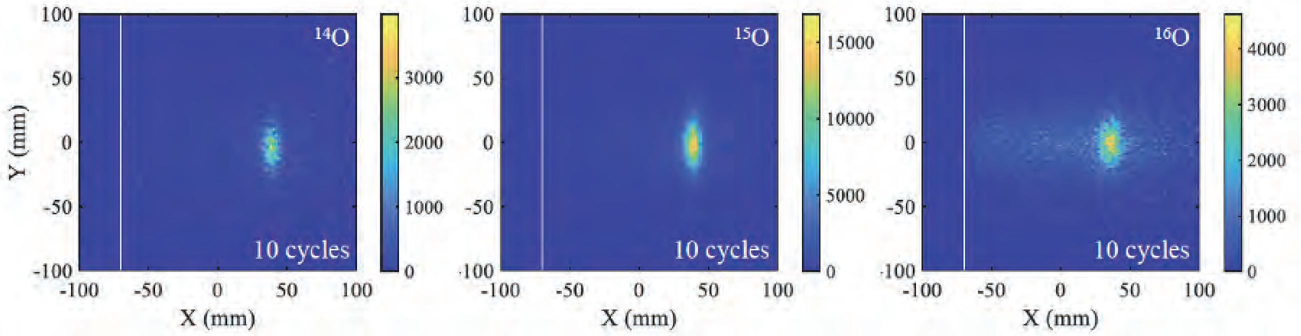

Figure 20. 2D PET images obtained during the high-energy implantation of oxygen isotopes in a PMMA phantom. The x and y axes represent the central plane of the beam, which also corresponds to the mid-horizontal plane of the scanner. The beam travels in the positive x-axis direction, and the beam entrance face of the phantom is marked by a white line. The color scale corresponds to the number of coincidence events. Figure reproduced from ref. [3], open access under CC-BY 3.0 license.

ICONIC

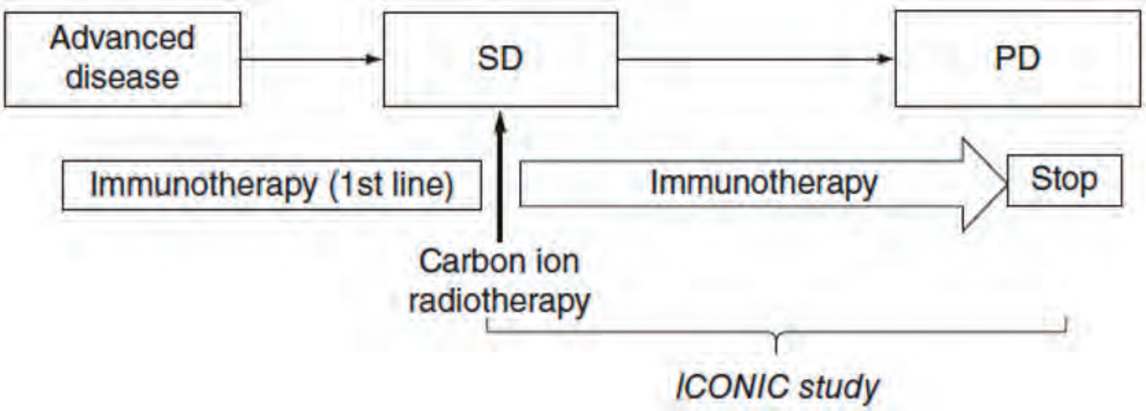

Figure 21. Study intervention. ICONIC: Carbon iON radiotherapy In solid Cancers with stable disease; PD: Progressive disease; SD: Stable disease. Figure reproduced from ref. [5], open access under CC-BY 3.0 license.

Combining of particle therapy with immunotherapy is one of the most promising strategies for the treatment of advanced cancers. However, while several pre-clinical experiments also performed at GSI show very exciting results [4], as yet no clinical translation has been implemented. We have now joined the first clinical trial combining C-ion therapy and immunotherapy, the ICONIC trial, that recently started at CNAO in Italy [5]. The trial includes stage-IV patients already treated with immunotherapy. After confirming disease stability and upon patient inclusion in the study, a hypofractionated carbon ion boost will be administered to one site of disease (Figure 21). Carbon-ion radiotherapy will be delivered at CNAO while molecular analysis on patients' blood will be performed at GSI.

Outlook for 2024

The year 2024 will be a tipping point for many activities in our Department. BARB will perform the crucial experiment aiming at demonstrating for the first time the possibility of treating a tumour in vivo with radioactive ion beams. Other exciting experiments in February with C-ions will be the MINOS project on immune effects of FLASH (a collaboration of three groups in our Department) and the study of the radiosensitivity of glioblastoma in a cerebral organoid model (Stem Cell group led by Insa Schröder). We will also perform the COMIX experiment in collaboration with CNAO in a mouse model of osteosarcoma. In April we will run the new experiments selected in the AO-IBPER call using 1 GeV/n Fe-ions and we will perform a cornerstone test for the Galactic Cosmic Ray (GCR) simulator, developed at GSI with ESA funding. If successful, the GCR simulator will be available to the IBPER investigators already in 2025. In June, we will use the Uranium beam to test space microelectronics in the framework of the EU project RADNEXT. In August, we will also host the 4th edition of the ESA-FAIR Summer School.

Selected publications of 2023

- [1] Graeff, C.; Volz, L.; Durante, M. Emerging Technologies for Cancer Therapy Using Accelerated Particles. Prog. Part. Nucl. Phys. 2023, 131, 104046. DOI:10.1016/j.ppnp.2023.104046
- [2] Kostyleva, D.; Purushothaman, S.; Dendooven, P.; Haettner, E.; Geissel, H.; Ozoemelam, I.; Schuy, C.; Weber, U.; Boscolo, D.; Dickel, T.; Drozd, V.; Graeff, C.; Franczak, B.; Hornung, C.; Horst, F.; Kazantseva, E.; Kuzminchuk-Feuerstein, N.; Mukha, I.; Nociforo, C.; Pietri, S.; Reidel, C. A.; Roesch, H.; Tanaka, Y. K.; Weick, H.; Zhao, J.; Durante, M.; Parodi, K.; Scheidenberger, C. Precision of the PET Activity Range during Irradiation with 10 C, 11 C, and 12 C Beams. Phys. Med. Biol. 2023, 68 (1), 015003. DOI:10.1088/1361-6560/aca5e8
- [3] Purushothaman, S.; Kostyleva, D.; Dendooven, P.; Haettner, E.; Geissel, H.; Schuy, C.; Weber, U.; Boscolo, D.; Dickel, T.; Graeff, C.; Hornung, C.; Kazantseva, E.; Kuzminchuk-Feuerstein, N.; Mukha, I.; Pietri, S.; Roesch, H.; Tanaka, Y. K.; Zhao, J.; Durante, M.; Parodi, K.; Scheidenberger, C. Quasi-Real-Time Range Monitoring by in-Beam PET: A Case for 15O. Sci. Rep. 2023, 13 (1), 18788. DOI:10.1038/s41598-023-45122-2
- [4] Helm, A.; Totis, C.; Durante, M.; Fournier, C. Are Charged Particles a Good Match for Combination with Immunotherapy? Current Knowledge and Perspectives. Int. Rev. Cell Mol. Biol. 2023, 376, 1–36. DOI:10.1016/bs.ircmb.2023.01.001
- [5] Cavalieri, S.; Vitolo, V.; Barcellini, A.; Ronchi, S.; Facoetti, A.; Campo, C.; Klersy, C.; Molinelli, S.; Agustoni, F.; Ferretti, V. V.; Silvestri, A. De; Platania, M.; Vecchio, M. Del; Durante, M.; Helm, A.; Fournier, C.; Braud, F. de; Pedrazzoli, P.; Orlandi, E.; Licitra, L. Immune Checkpoint Inhibitors and Carbon ION Radiotherapy In Solid Cancers with Stable Disease (ICONIC). Futur. Oncol. 2023, 19 (3), 193–203. DOI:10.2217/fon-2022-0503

3. Research of the Compressed Baryonic and Quark Matter Departments Departments

Coordination: Prof. Dr. Joachim Stroth (Goethe-Universität Frankfurt, Helmholtz-Institut & GSI)
Authors: Tetyana Galatyuk, Silvia Masciocchi, Joachim Stroth

The division conducts research on extreme states of strong-interaction matter in the laboratory by colliding heavy ions at center of mass energies between 2.5 GeV and 5 TeV. While the CBM and HADES departments act as host labs for the future Compressed Baryonic Matter experiment and the High-acceptance Di-electron Spectrometer operational at SIS18, respectively, the ALICE department serves as a hub for the German participation in ALICE at the LHC. The research activities include the study of properties of the quark-gluon plasma, the search for novel phases of strong-interaction matter including landmarks of the phase diagram like a conjectured first-order phase transition or the related critical point. The studies include also aspects of nuclear and hadron physics. In particular the latter profits from a secondary pion beams available at SIS18 in combination with the HADES spectrometer.

The department cooperate in the application of different analysis techniques, like e.g. the KF Particle Finder, for the reconstruction of weakly decaying particles via their decay products or the extraction of event-by-event observables to search for signs of criticality. Common interest also exists in the development of next-generation CMOS pixel sensors, a technology, which has been identified by the community for the next generation inner tracker of ALICE (ITS3) and for a potential upgrade of the CBM tracking system. Such activities are carried out in close collaboration with the Detector Laboratory of GSI.

3.1 ALICE at GSI

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

ALICE is one of the four large experiments at the Large Hadron Collider (LHC) at CERN (Geneva). Its aim is to study the physics of strongly interacting matter by colliding heavy ions at ultrarelativistic energies. In such collisions, an extreme phase of matter – the quark-gluon plasma (QGP) – is formed. Our universe has been in such a state for the first few microseconds after the Big Bang before quarks and gluons were bound together to form protons and neutrons. As the universe expanded and the temperature dropped to roughly a hundred thousand times that of the core of the Sun, hadrons formed. By recreating this primordial state of matter in the laboratory and learning how it evolves, ALICE studies at the same time the earliest history of the universe and the mechanism that confines quarks and gluons. A compendium of current ALICE results can be found in Ref. [1].

The ALICE team at GSI is the third largest among the 172 ALICE teams currently active. By now it has been playing a leading role in most aspects of the collaboration for nearly three decades. 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.

The current focus of the ALICE group at GSI is on the operation, calibration, and optimization of the upgraded TPC, as well as on physics data analysis and in particular the preparation for the high-statistics data coming from the present measurement campaign. Below we report the performance of the upgraded experiment and list several physics highlights published in 2023.

Performance of the upgraded ALICE in Run 3

After the successful ALICE operation in LHC Run 1 (2009-2012) and Run 2 (2015-2018), the experiment was upgraded to cope with the increased LHC luminosity planned in Run 3 (2022-2025). The ALICE team at GSI has been strongly involved in the upgrade of the Time Projection Chamber, the main tracking and particle-identification detector of ALICE. The readout chambers covering both ends of the TPC cylinder were completely rebuilt. The previously used gating grid has been eliminated and the flow of gas-amplification ions into the TPC drift volume is instead kept low (< 1%) by a sophisticated configuration of electric fields in stacks of four gas electron multiplier (GEM) foils. With this, the TPC can work continuously (no dead time) and, read out by a dedicated new data acquisition system, record Pb-Pb collision events at a rate of 50 kHz, which is equal to the peak collision rate planned in Run 3. The new chambers were tested in the laboratory and at the Gamma Irradiation Facility at CERN, and the remaining big question was how they would behave in the actual high-luminosity running at the LHC.

In 2023, the LHC delivered proton-proton collisions from April till July and Pb-Pb collisions in October. The proton-proton center-of-mass collision energy was 13.6 TeV. In Pb-Pb collisions, the energy was 5.36 TeV per pair of colliding nucleons.

In the proton-proton running, the interaction rate at ALICE was kept at 500 kHz by displacing the colliding beams such that their overlap was only partial. In addition, several runs were taken at rates up to 4 MHz, in order to simulate the load expected in ion-collision running. As shown in Figure 22 left, the integrated luminosity recorded in Run 3 reached 28 pb^{-1}. Figure 22 right shows the excellent particle identification by means of their specific energy loss in the TPC. The number of events collected in Run 3 exceeds by two orders of magnitude the total statistics from Runs 1 and 2.

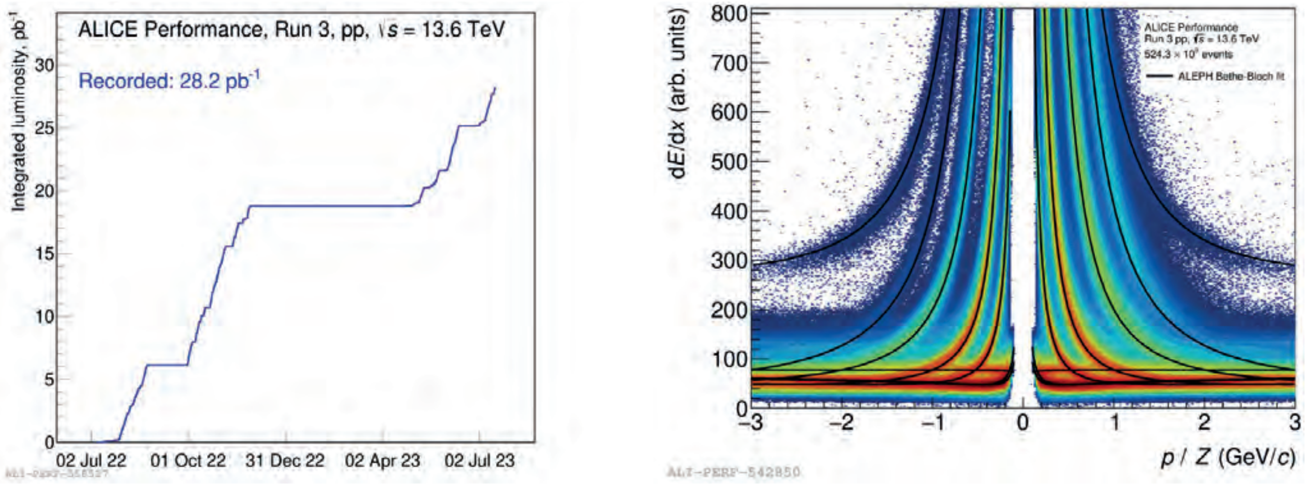

Figure 22. **Left: integrated proton-proton collision luminosity recorded by ALICE in the LHC Run 3. Right: particle identification by the specific energy loss in the ALICE Time Projection Chamber.**

The measurements of heavy flavors and composite particles are particularly profiting from the increased sample. Two cases, D^0 and antihelium nuclei, are shown in Figure 23:

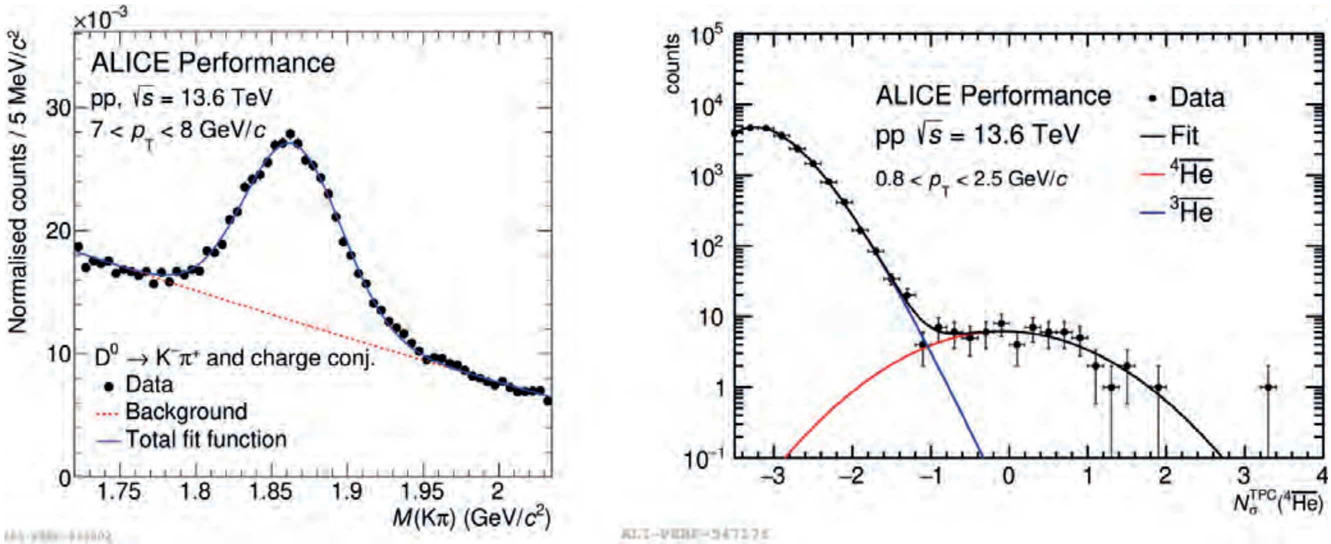

Figure 23. **Left: D^0 peak in the kaon-pion invariant-mass spectrum collected so far in Run 3. Right: antihelium peaks visible in the specific energy loss spectrum in the TPC. (The energy loss is shifted such that the antihelium-4 peak sits at zero, and scaled such that its standard deviation is 1.)**

In Pb-Pb running, ALICE recorded collisions up to 47 kHz, the maximum interaction rate offered by the LHC. As shown in Figure 24, 12 billion events were recorded. This is 40 times more than the total minimum-bias sample from Run 1 and Run 2. The maximum data readout rate was about 800 GB/s.

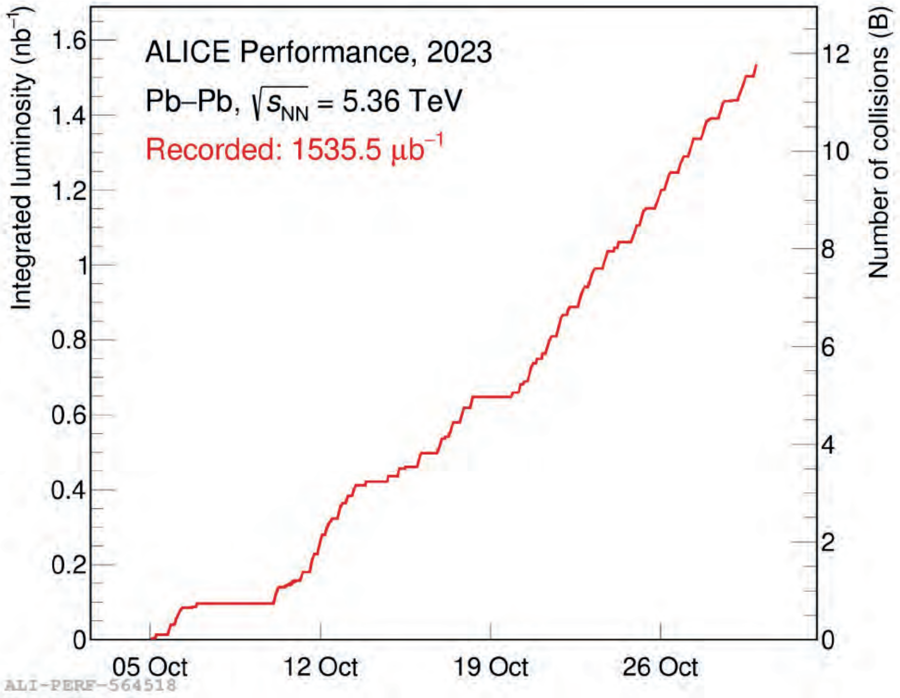

Figure 24. **The Pb-Pb collision data recorded so far in Run 3. The number of events is 40 times higher than the total minimum-bias sample collected in Runs 1 and 2.**

Concluding, the upgrade of the ALICE TPC was successful, both the data rate and data quality are as anticipated. The next major challenge is the calibration. The ALICE team at GSI is strongly involved in this effort.

Selected highlights from 2023

In 2023 the ALICE collaboration submitted 53 articles for publication. In 15 cases members of the GSI team were directly involved in writing. Below we briefly discuss a few highlight results.

Unlike in the baryon-dominated world that is surrounding us, at LHC energies the symmetry between matter and antimatter is restored – as expected when creating particles out of pure energy. The yields of particles and antiparticles at midrapidity agree within 1%. This finding, and its discussion in terms of the chemical potential, are the topic of Ref. [2].

Light (anti)nuclei are produced copiously by coalescence between (anti)nucleons. Since the yields of nucleons and antinucleons are similar, also nuclei and antinuclei are produced at nearly equal rates. The measurement of the interaction of antihelium-3 with ALICE detector material [3] allows one to estimate the absorption of this particle in the universe and thus to interpret the antihelium-3 measurements done by AMS. Similar analyses were performed for antideuteron and antitriton.

Hypertriton ${}^{3}_{\Lambda}$H, a compound system of proton, neutron, and hyperon (pnΛ), is a particularly interesting light nucleus that is copiously produced in Pb-Pb collisions at the LHC. It is a loosely (~100 keV) bound deuteron-hyperon molecule, and its size (~10 fm) is comparable to the total size of the collision system. The world's most precise measurement of hypertriton's lifetime and its Λ separation energy, just published by ALICE [4], is shown in Figure 25.

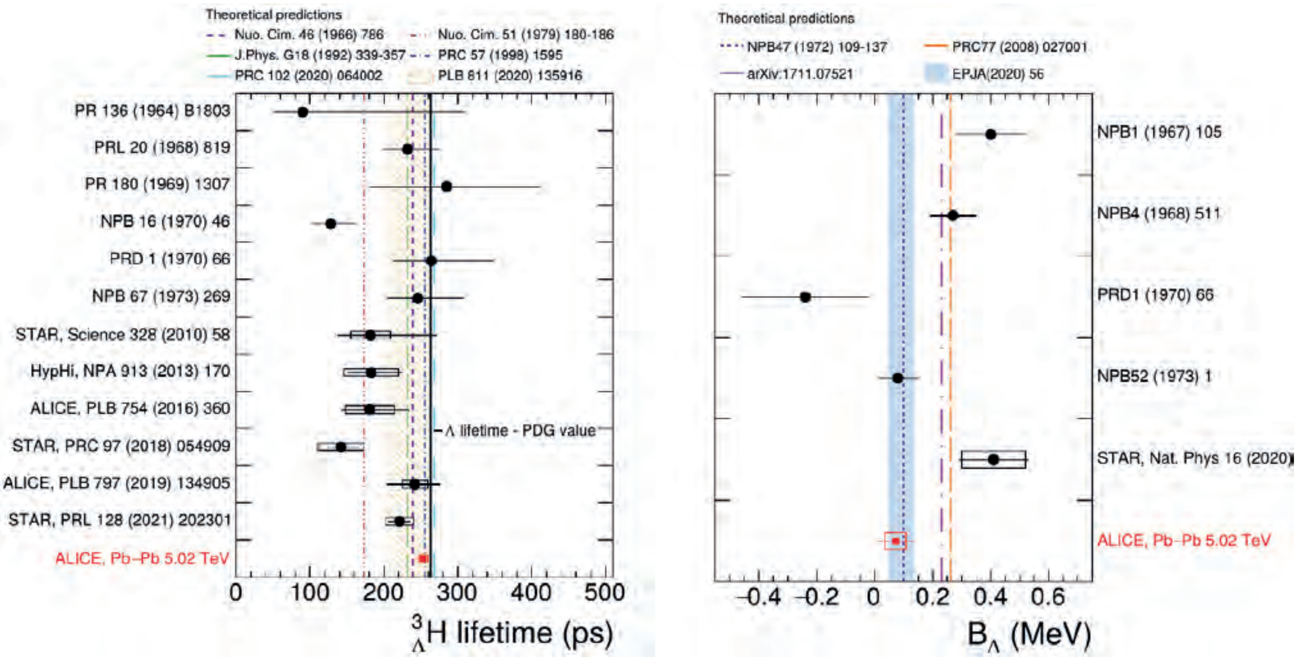

Figure 25. The world's most precise measurement of hypertriton's lifetime and binding energy [4].

Like nucleons coalesce into nuclei, independently created charm and anticharm (c and cbar) quarks can coalesce into a J/ψ meson. This production mechanism, predicted more than two decades ago, is clearly visible in the recent high-statistics measurement by ALICE [5]. The J/ψ yield is enhanced at low transverse momentum at midrapidity in central collisions, where the charm density – and with it the coalescence probability – is highest. The enhancement at low transverse momentum is shown in Figure 26.

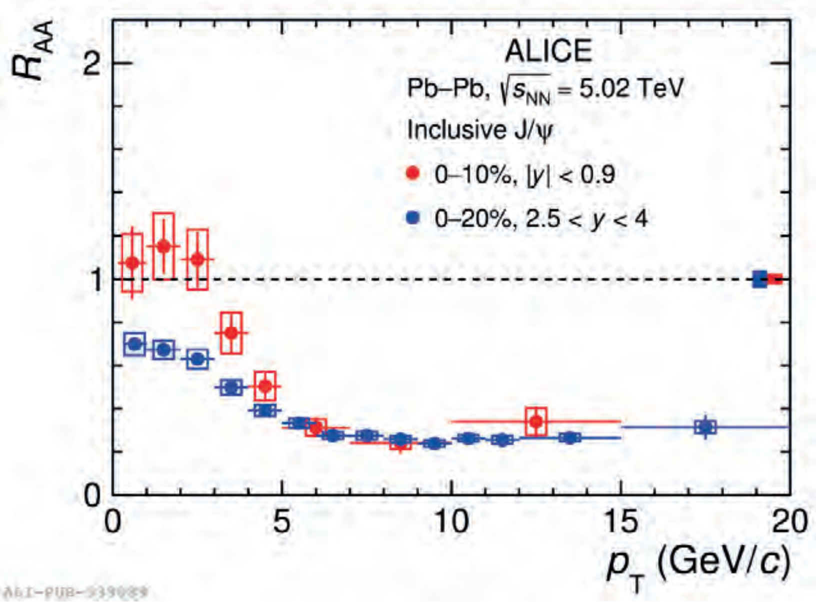

Figure 26. J/ψ production by coalescence of c and cbar quarks in central collisions [5]. As predicted, the additional component is visible in central collisions at midrapidity and low transverse momentum, where the charm density is highest.

The understanding of charm hadronization improves with every further measurement of charm-carrying hadrons, the most recent one described in Ref. [6]. The main observation is that the fragmentation fractions, the distribution of charm among final hadrons, depend on the environment – in proton-proton collisions the fraction of charm carried away by baryons is clearly higher than in e^+e^- collisions (Figure 27 left). Summing up yields of all charmed hadrons one arrives at a solid measurement of the total cross section for charm production (Figure 27 right). The non-universality of fragmentation was also observed for beauty.

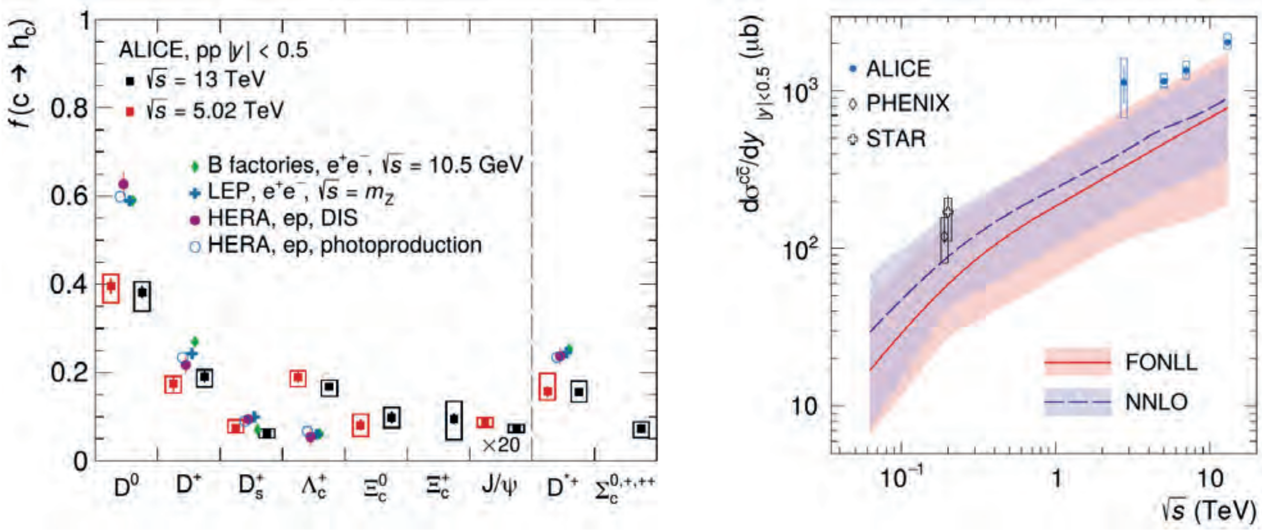

Figure 27. Charm fragmentation fractions (left) and charm production cross section (right) in pp collisions [6].

Selected publications of 2023

- [1] ALICE Collaboration: The ALICE experiment – A journey through QCD, arXiv:2211.04384 [nucl-ex].
- [2] ALICE Collaboration: Measurements of chemical potentials in Pb-Pb collisions at 5.02 TeV, arXiv:2311.13332 [nucl-ex].
- [3] ALICE Collaboration: Measurement of anti-3He nuclei absorption in matter and impact on their propagation in the Galaxy, Nature Physics vol 19 (2023) 61, arXiv:2202.01549 [nucl-ex].
- [4] ALICE Collaboration: Measurement of the lifetime and Λ separation energy of 3ΛH, Phys. Rev. Lett. 131 (2023) 102302, arXiv:2209.07360 [nucl-ex].
- [5] ALICE Collaboration: Measurements of inclusive J/ψ production at midrapidity and forward rapidity in Pb–Pb collisions at 5.02 TeV, arXiv:2303.13361 [nucl-ex].
- [6] ALICE Collaboration: Charm production and fragmentation fractions at midrapidity in pp collisions at 13 TeV, arXiv:2308.04877 [hep-ex].

3.2 CBM at FAIR

Head: Prof. Hans Rudolf Schmidt (GSI & Univ.Tübingen)
Authors: Alberica Toia (GSI & University of Frankfurt), Christian Sturm, Ilya Selyuzhencov

The primary objective of the CBM experiment at FAIR is to investigate the behavior of nuclear matter under extremely high baryonic density conditions. This involves studying the high-density equation of state (EoS), exploring the transition to a deconfined and chirally restored phase, and identifying the critical endpoint. The enhanced production of multi-strange (anti-)particles serves as a promising diagnostic probe for this novel state. The CBM detector is specifically designed to measure these rare diagnostic probes with unparalleled precision and statistical significance. Key observables of significance include the production of hypernuclei. The discovery and examination of new (doubly strange) hypernuclei and hyper-matter will contribute valuable insights into hyperon-nucleon and hyperon-hyperon interactions.

Highlights & Activities in 2023

Evaluation of the physics performance at very low beam energies

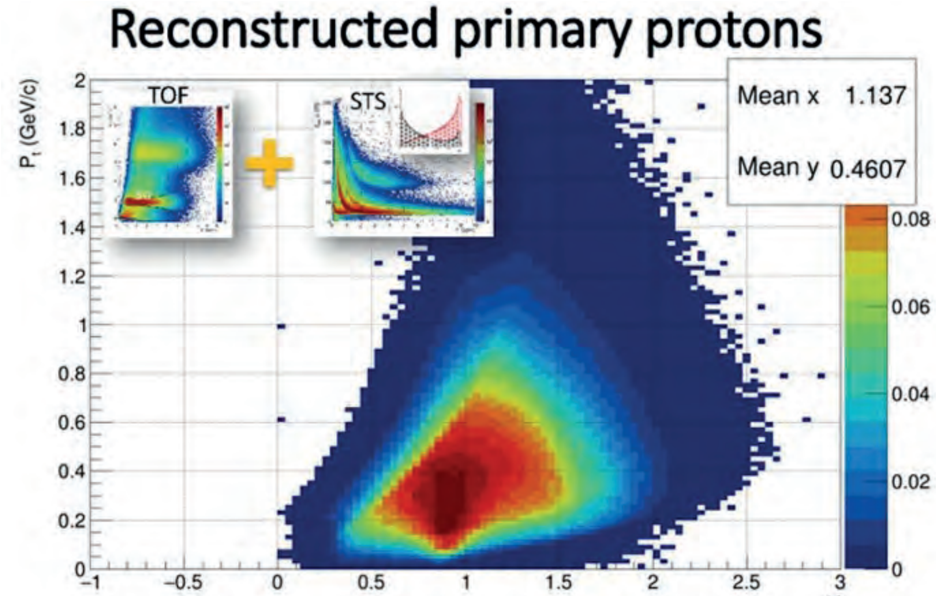

Figure 28. Reconstructed primary protons for central Au+Au collisions at 2.78 AGeV. Using the STS dE/dX measurements allows significantly increased CBM acceptance at negative rapidity.

The delves into the reconstruction performance of primary protons in Au+Au collisions, extending down to the lowest FAIR energies (2 AGeV). Two models, UrQMD and DCM, are employed to investigate the capabilities. The focus is on assessing the CBM detector's acceptance, incorporating the (baseline) tracking detector STS and PID detectors TRD and TOF, with half of the nominal magnetic field applied. Proton identification relies on the TOF detector. Notably, employing dE/dX measurements with the STS detector significantly enhances the efficiency of reconstructing primary protons, particularly for those with low momentum. Efficiency correction matrices are calculated using multi-differential p_t versus rapidity distributions. The simulation results are illustrated in Figure 28.

Performance for the measurement of strange hadrons and hypernuclei at 3.85 and 5.75 AGeV Au+Au

Performance studies regarding the production of strange hadrons and hypernuclei in Au+Au collisions at 3.85 and 5.75 AGeV with the CBM experiment at FAIR are depicted in Figure 29. A comparison is made between the CBM performance and that of the STAR experiment, and projections for statistical uncertainties with high statistics data at CBM are presented. The PHQMD model, a novel microscopic N-body transport model for heavy-ion collisions, is employed for simulating strange hadron and hypernuclei production. The advanced KFParticle Finder package is utilized for reconstructing the decay topology of strange hadrons and hypernuclei. To identify hypernuclei, heavy fragments such as d, t, ^{3}He, and ^{4}He are identified using the TOF detector. Similar to protons, the use of dE/dx measurements with the STS detector significantly reduces combinatorial background. Monte-Carlo simulations incorporate both hard and soft Equation-of-States. The availability of high-statistic data enables the study of key observable distributions in multi-dimensions.

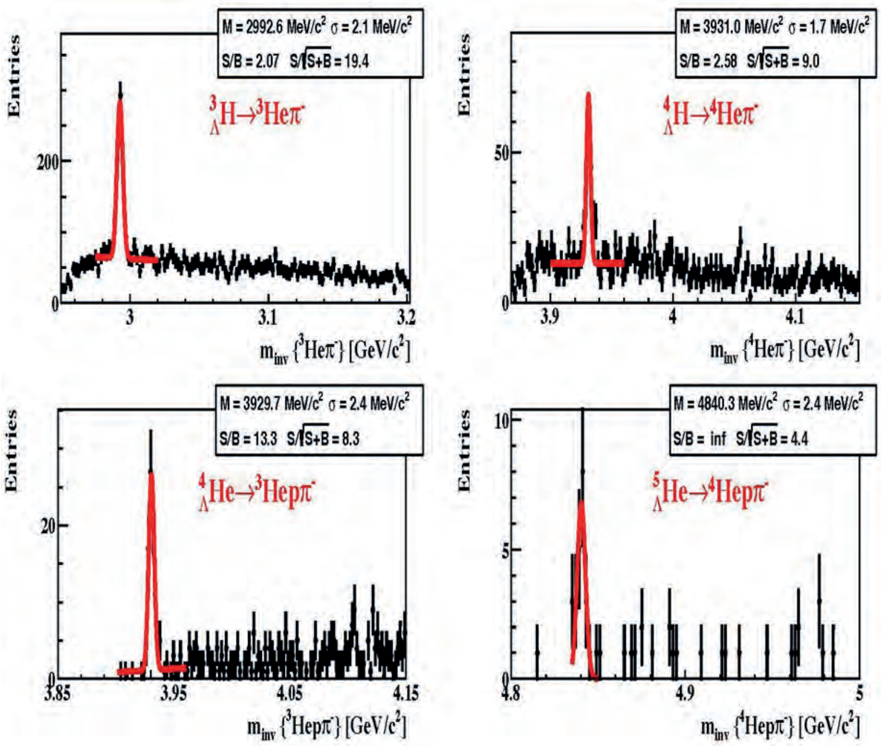

Figure 29. Reconstructed invariant mass distribution of two and 3-body decays of hypernuclei in central Au+Au collisions at 5.75 AGeV, the red line indicates the signal plus background fit by a polynomial plus Gaussian functions.

The STS Detector of the CBM Experiment

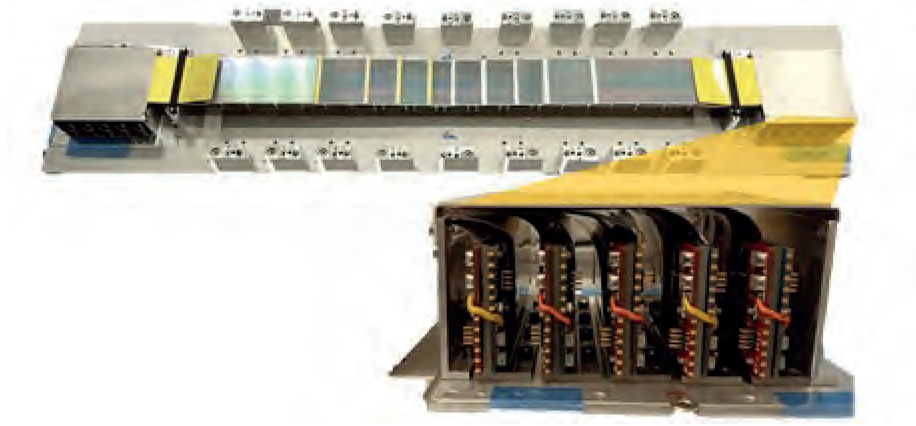

Figure 30. One of the first ladders of the series production on its mounting jig; the insert shows details of the FEB-box.

During this reporting period, substantial progress has been achieved in the development of the core detector for the CBM experiment, the Silicon Tracking System (STS). Notably, the series production of the fundamental components of the detector, namely the silicon modules and ladders, has gained significant momentum. Currently, the assembly of silicon modules is being carried out at both GSI and KIT. These modules, comprising the silicon sensor, micro-cables, and front-end readout boards, undergo thorough testing and a final burn-in sequence. Once these processes are completed, the modules are ready for installation onto the carbon fiber ladder. Figure 30 shows one of these ladders mounted on its assembly fixture which guarantees precise positioning of the sensor module. The insert gives account to the front-end electronics box, which holds the front-end boards glued onto cooling fins.

In parallel, the engineering design of the general STS detector structure is being completed. This structure encompasses a thermal insulation box, eight layers of silicon tracking stations, comprising 20 C-frames. Additionally, it features a sophisticated air and liquid cooling system for sensors and front-end electronics, the necessary power and readout boards, and a complex network of readout and supply cables, all well as feed-through panels. The final engineering 3D model is shown in Figure 31.

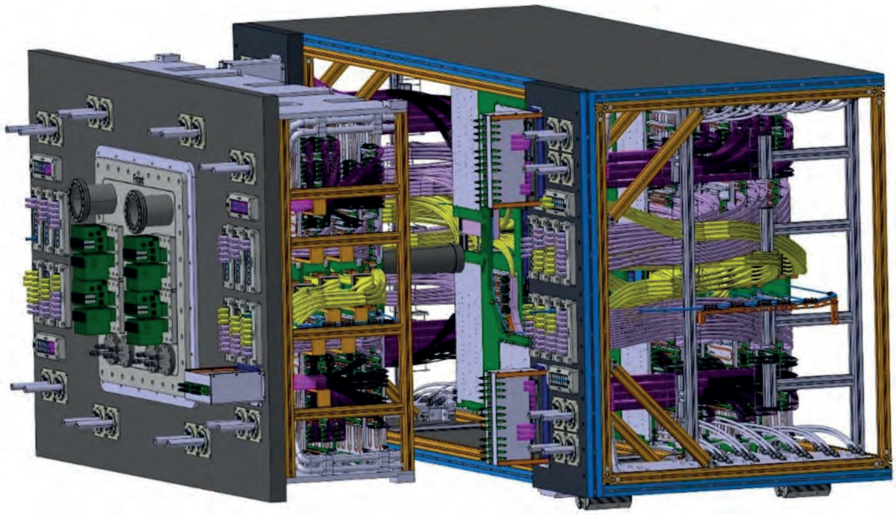

Figure 31. 3D-CAD drawing of the STS assembly.

Another crucial component of the detector assembly is the carbon fiber beam pipe, which simultaneously functions as the vacuum window for enclosing the Micro-Vertex Detector (MVD). This renders the beam pipe a highly intricate structure, presenting challenges both in terms of manufacturing and ensuring its structural integrity. A prototype of the beam pipe manufactured in industry is shown in Figure 32.

Figure 32. Prototype of the STS section of the CBM vacuum beam pipe.

FAIR Phase-0: Next steps with mCBM towards CBM

With the data taken in 2022, rare Λ baryons were reconstructed with the mCBM experiment, proving the free-streaming data acquisition concept of CBM as well as demonstrating the rare probe capability involving the full CBM data chain. In 2023, the focus was placed on (1.) developing the CBM online system for real-time reconstruction and selection in a computer farm, (2.) designing and performing major upgrades of the detector subsystems for mCBM experiments in 2024 and (3.) optimizing the CBM offline data analysis chain in terms of calibration, alignment, hit finding and track reconstruction. For the latter, Figure 6b shows an event display of a track found by the CBM CA (Cellular Automaton) track reconstruction algorithm which was applied to mCBM 2022 data, taken in Ni+Ni collisions at 1.93 AGeV kinetic bombarding energy. Tracks were formed from hits in the Silicon Tracking System (STS), the Transition Radiation Detector (TRD1D and -2D) and the Time-of-Flight wall (TOF). The primary interaction vertex was reconstructed from the intersection of the track projection with the target plane, shown in Figure 33 (a). Performance tests and further optimizations of the CA track reconstruction algorithm as well as the alignment approach are ongoing.

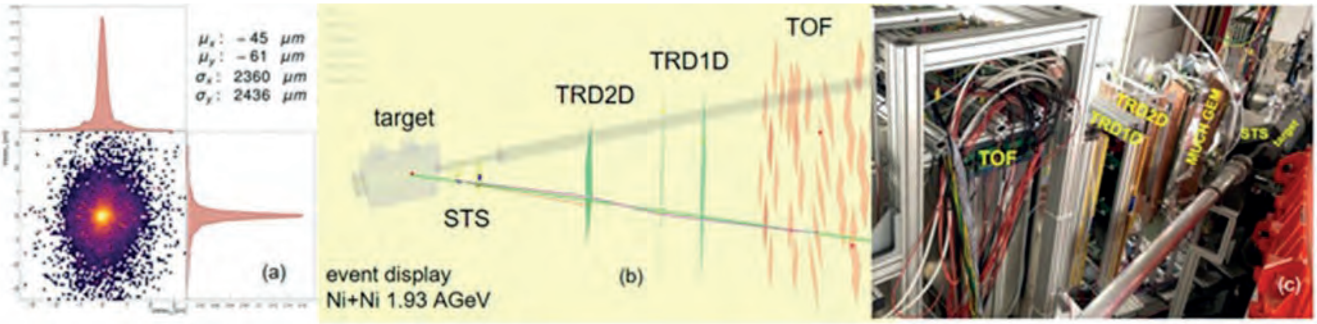

Figure 33. Vertex reconstruction with mCBM (a), event display (b) and photograph (c) of the mCBM setup in 2022. The CBM CA (Cellular Automaton) track reconstruction algorithm was applied to the mCBM 2022 data - tracks were formed from hits in STS, TRD (TRD2D and TRD1D) and TOF.

Since CBM will cope with unprecedented collision rates up to 10 MHz, systematic rate capability studies of the detector subsystem are an essential part of the mCBM program. Here, a distinct micro-spill structure of the slow-extracted SIS18 beam was observed within the 2022 data resulting to intensities peaked by a factor about 10 (and above). At average collision rates in the MHz-range, the front-end ASICs were partially driven into saturation and thus suffered data loss, which significantly challenge the investigation on saturation effects of the detector systems. Hence, further rate scans up to highest collision rates will be performed during the 2024 beam campaign. First beam tests dedicated for the TOF detector system were carried out in December 2023 during the machine engineering run, the data analysis is ongoing. Furthermore, a spill-smoothing cavity installed within SIS18 as well as a beam feedback-system might significantly reduce the micro-spill structure of the slow-extracted SIS18 beam. Both systems were successfully tested during the machine engineering run in November/December 2023.

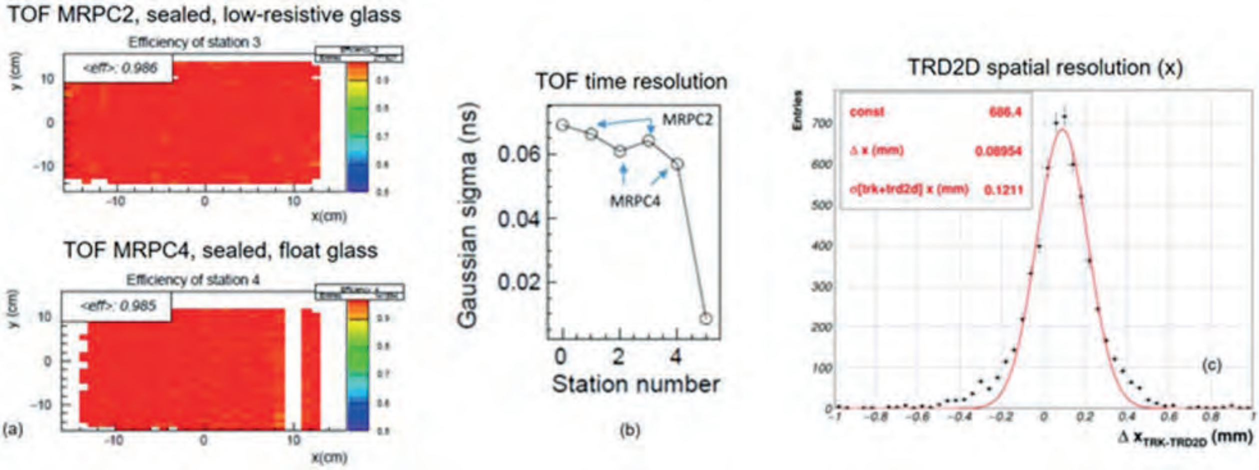

Figure 34. Results on detector performance: detection efficiency (a) and time resolution (b) of TOF RPC modules as well as spatial resolution of the TRD2D detector (c).

Examples for results on detector performance studies are depicted in Figure 34. The data were taken in U+Au collisions at 1.06 A GeV (a), (b) in March 2022 and (c) in Ni+Ni collisions at 1.93 A GeV kinetic projectile energy (May 2022). Both were measured at moderate collisions rates of about 400 to 500 kHz (averaged). The TOF RPC modules show detection efficiencies of about 0.98 (a) with a time resolution of approx. 60 ps (b). Additionally, the spatial resolution of the TOF RPC modules were determined to 2.5 mm across and 3.5 mm along strips. The spatial resolution of the TRD2D detector station, a MWPC equipped with triangular-shaped read-out pads for 2-dimensional position measurement, was determined to approx. 100 µm, see Figure 34 c, The obtained results are in good agreement with the design specifications of the corresponding CBM detector systems.

Major upgrades of the detector systems have been launched for upcoming mCBM experiments in 2024. The STS will be additionally equipped by a third station (station-0) positioned upstream (see Figure 35 a). The new STS station comprises a 6x6cm^2 Si-strip sensor read out by a FEB8-5 front-end board (), which provides a 5-times higher bandwidth. The first station of the TRD detector system (TRD2D) will be fully equipped with pre-series read-out electronics, while the two TRD1D stations (type-8, 768 channels each) will be substituted by stations with significantly enhanced granularity (type-5, 3456 channels each). Furthermore, a second RPC wall will extend the TOF system. In the new TOF configuration, all RPC modules of the double wall will be aligned horizontally. Additionally, two test systems consisting of prototype modules of the Forward Spectator Detector (FSD), see Figure 35 c, as well as of the (Jülich) Neutron Calorimeter (NCAL), see Figure 35 d. The mobile test systems will be positioned under 25° downstream the TOF system and under 0° close to the beam dump.

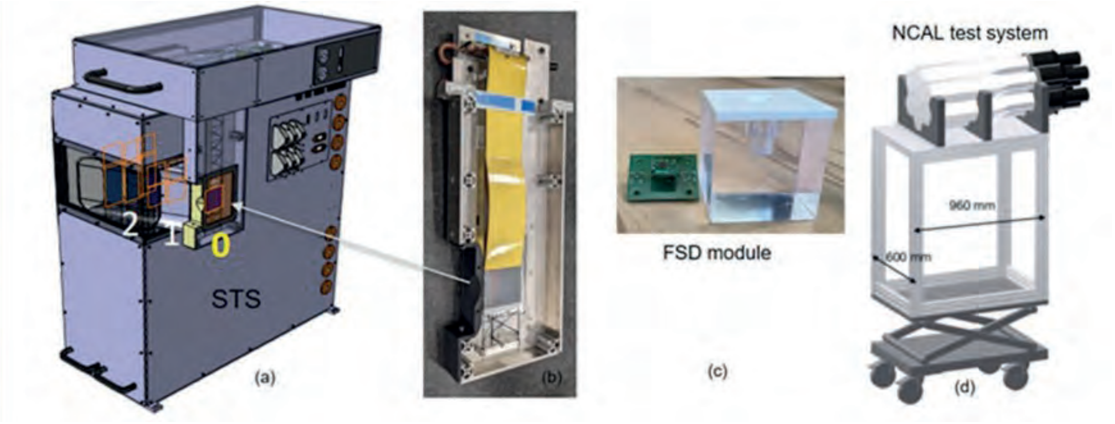

Figure 35. Upgrade of detector systems for mCBM experiments in 2024.

One major task for the mCBM experiments in 2024 is to test a prototype online system for CBM. Hence, two stages of the online system are being developed. The first involves the unpacking of the detector system data, followed by an event building via time-cluster search (DigiEvent building). A second stage includes additionally hit reconstruction for STS, TRD and TOF, reconstruction of tracks by the CA track reconstruction algorithm, and on top, a selection of events containing Λ baryon candidate(s). Development, optimization and tests of the prototype online system within data challenges are ongoing.

Outlook for 2024

In 2024, module and ladder series production will continue, the assembly of tracking stations will start. The CBM-STS has to pass production readiness reviews, where the functional operation of ladders will be demonstrated, based on the characterization and test of the first 3 series ladders. Together with our associated collaborators at KEK, the E16 experiment at J-PARC will operate and test in beam 10 STS-modules to gain insight into the system performance, and eventually its application to the physics program. A new STS module will be installed in the mCBM experiment, upstream to the existing modules, covering the full acceptance of the next 2 stations, featuring 5 uplinks per ASIC. This will allow to test the performance of the FEB8-5, designed to sustain the maximum rate achieved in the final detector, and to increase the acceptance for potential physics analyses.

Selected publications of 2023

The publications will be reported separately.

3.3 HADES

Head: Prof. Dr. Joachim Stroth (Goethe-Universität Frankfurt & GSI)
Authors: Tetyana Galatyuk, Jerzy Pietraszko, Anar Rustamov, Joachim Stroth

Last year's activities were essentially determined by three projects: the conversion of the HADES spectrometer back into the configuration for experiments with heavy ions, the consolidation of the event reconstruction software including the new forward detector setup used in the pp beam time in 2022 as well as the related alignment of the detectors, and a campaign to find measures for reducing systematic uncertainties in the comparison of inclusive hadron data with respective calculation using microscopic transport calculations. A highlight has been the publication of the final results on the exclusive reaction π^-+ p -> $n_{miss.}$ + e^+ + e^-, which not only represents the first measurement of an electromagnetic transition form factor of a baryon in the time-like region, but also demonstrates the huge scientific potential of the combination of a pion beam with a high acceptance dilepton spectrometer. These results, which were already presented in a preliminary state in the last annual report, can now be found in a combined publication in Physical Review Letter and Physical Review A, separating the key experimental result from the complex analysis behind it, respectively.

In 2022, the HADES collaboration welcomed a Czech group from University of Olomouc and a group from Uppsala University, Sweden, as new collaboration members. They gratefully accepted responsibility for the forward wall, a hodoscope measuring approximately two by two square meters, which is used in heavy-ion experiments to determine the centrality of the reaction and the reaction plane. Remarkable is also the completion of electromagnetic calorimeter, a system in the responsibility of the Czech team from the Institute for Nuclear Physics, Czech Academy of Science in Rez. Modules are also recycled in this detector, as the lead crystals were already used in the OPAL detector at LEP, CERN. The calorimeter shows the expected performance as is depicted in Figure Figure 37.

Preparation for FAIR Phase-0 experiment G-22-00022

By end of 2023 HADES has been completely reconfigured and was ready for data taking in the upcoming beam time G-22-00022 addressing heavy-ion collisions at energies below 1 A GeV beam energy. The goal is to extend the excitation function of rare probes and event-by-event observables towards higher baryo-chemical potential, i.e. to lower beam energies. According to theoretical conjectures, such observables should be sensitive to effects originating from criticality due to first-order phase transitions in the equation-of-state of strong-interaction matter. Some of the achievements are briefly described below.

New controls for the HADES superconducting magnet

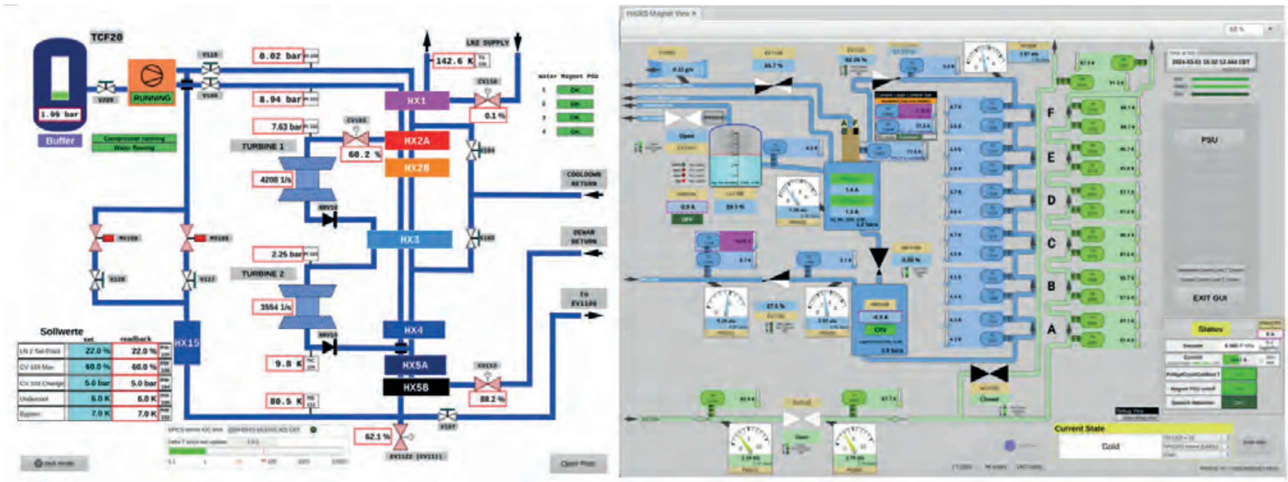

Figure 36. (left panel) User interface of the control of the HADES cryo-plant. Note the high revolution frequencies of the turbines reaching to around 4000 Hz. (right panel) The flow of super-critical Helium through the six coils of the HADES magnet (A-F) colored in blue, while the Nitrogen thermal shield is sown in green.

The heart of the HADES spectrometer is the six-coil super conducting toroidal magnet. A specialty of that magnet is the efficient cooling using super critical helium. Each of the six coils is made of 140 rounds of super conducting wire through a maximum electric current of 3464 A flows. Each coil is housed in an individual case and embedded in a liquid-nitrogen shield at 87 K. The coils are cooled further down to 4.7 K with Helium at a pressure about 0.29 MPa, i.e. above the critical point thus preventing bubbles to form while the Helium is flowing through the thin tubes. At the outlet, Helium is finally liquified when streaming across the current lead section of the magnet. At the time the magnet was installed in the HADES cave, together with a recycled cryo-plant on its roof, the latter had already been in operation at the Bessy Synchrotron for years. Now, after 20 years, it was high time to replace the old control units and software, which was still running on old Windows computers and for which no spare parts were available on the market. Due to incomplete documentation of the recycled cry-plant, re-engineering had to be done for some parts. The user interface and control software are now based on and EPICS, respectivel. Figure 36 shows a screen shot of the user interface for the controls of the cryo-plant and the magnet cooling in the left and right panel respectively. As is seen in the right panel of Figure 36, the magnet is in its cold state and the temperature reading at the coils (A–F) shows values between 4.3 and 4.7 K, at a pressure of 2.87 atm, conditions, under which Helium is super critical. The green side shows the conditions of the Nitrogen shield. The maximum required cooling power of the cold mass is 100 W, a number, which reaches close to the specified capacity of the plant of 110 W. The left panel shows the control of cryo-plant, with its two turbines which provide cooling power to at low temperature realized by mechanical work.

Completion of the Electromagnetic Calorimeter

Just in time for the gold run 2024, also the last of six sectors of the lead-glass calorimeter could be completed thanks to the effort and resources realized by our Czech collaborators from INP CAS in Rez. The calorimeter, which is based on recycled lead glass modules formerly used in the OPAL calorimeter at the LEP, CERN, is equipped with new PMTs and a TRB read-out system using FPGA-based time-to-digital conversion and amplifiers with charge-to-time circuits (PaDiWa boards). In HADES-IMG2 two invariant mass distributions are shown which have been analyzed after a first round of calibration of the system. The distributions were obtained from data taken for the p+p (4.5 GeV) beam time in 2022 and shows the performance of system at the time five sectors were complete. We observe mass resolution for the π^0 of 10%, which is close to the value from simulation of 9%. For both mass regions the study of the background is ongoing,

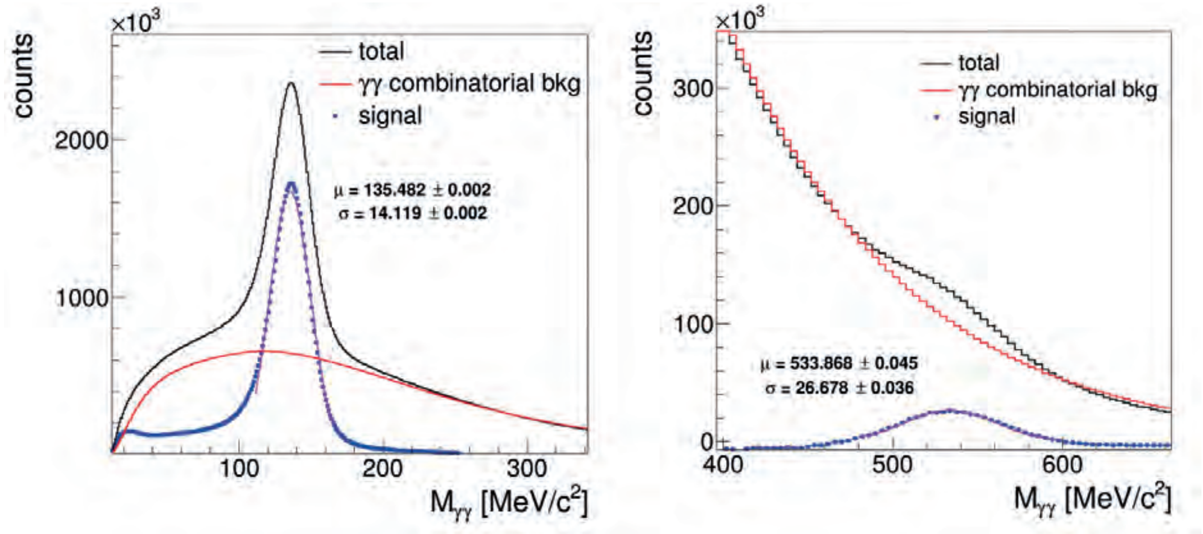

Figure 37. Invariant mass distributions for photon pairs detected in the ECAL in the p+p (4,5 GeV/ run. Preliminary mass resolutions are extracted using simple fits with Gaussians to the peak distribution. The background description is still subject to further studies.

Advanced Time-zero detectors

The 2024 beam time consist of a short run for the C+C collision system and a long run of three weeks for the system Au+Au. Due to the substantially different ionization power of the two ions of almost a factor 200, two different T0 detector had to be prepared. Both systems are based on Chemical Vapor Deposited diamond material.

For the p+p beam time in 2022, a start detector based on Low Gain Avalanche Diode (LGAD) principle was used. The sensor material was produced by Bruno Kessler Foundation in Trento and metallized at GSI Detector Laboratory. Exposed to the well-focused proton beam of 10^8 protons per second in the flat top, a non-ionizing dose of around to 10^{14} n_{eq} is accumulated per day beam on target." This dose reaches the known radiation hardness limit of the sensors. As a consequence, continuous gain loss was observed over the days and the irradiated area of the sensor changed by moving the detector minimally in the transverse direction with respect to the beam position. This damage required adjustments of the thresholds during the run and a detailed walk correction off-line to recover the intrinsic resolution of the sensors. A sophisticated correction procedure has been applied to the data for sub-regions in real time as short as 3 min.

The same sensor technology is used for a novel application in radio therapy. The idea is to measure the Relative Stopping Power (RSP) in ion beam treatment by precise measurement of the change of the ion velocity with high timing precision. This technique has the potential to revolutionize the Ion Computed Tomography (iCT) as the relevant information is obtained without using a residual energy detector [F. Ulrich-Pur et al.; e-print:2312.15027].

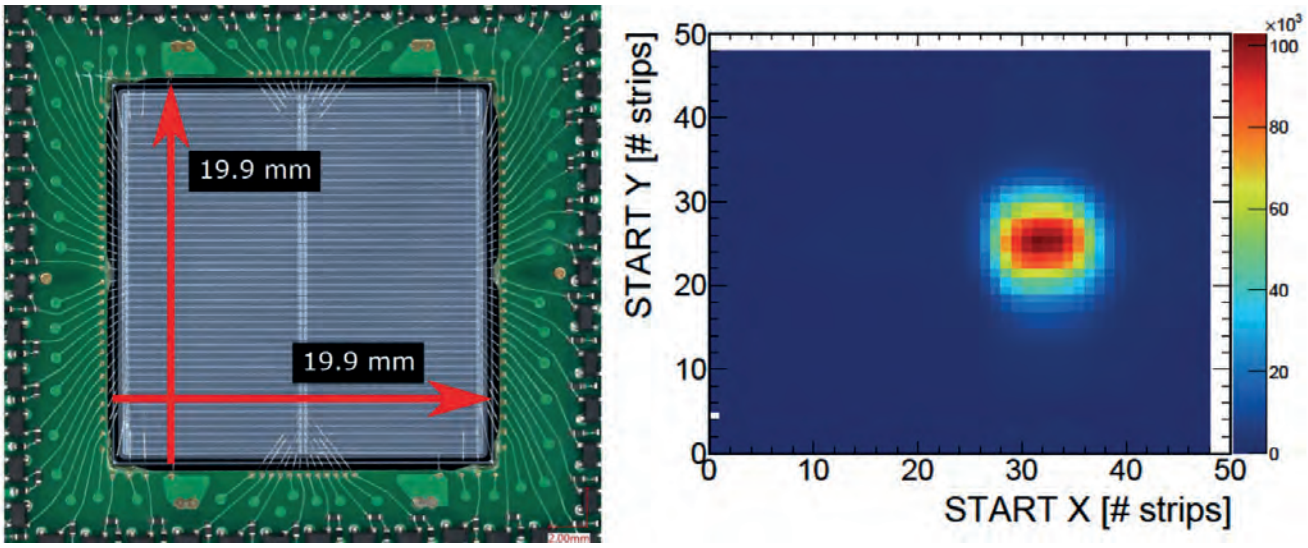

Figure 38. (left panel) Photo of the LGAD sensor used for time-zero (T0) determination for minimum ionizing beams. Each side has two columns of 48 400-µm-wide strips and a relative orientation of 90°. (right panel) Beam profile on the T0 detector in the p+p beam time in Spring 2022.

Bayesian Particle Identification of event-by-event observables

Event-by-Event fluctuations of baryon number have been studied in Ag-Ag collisions at beam kinetic energy of 1.58A GeV. For the first time a new technique based on Bayesian particle identification, the Identity Method [Phys. Rev. C 86 (2012) 044906], was applied to reconstruct cumulants of proton number distribution. In doing so a dedicated method was developed for a functional representation of detector response functions. Specifically, the measured inclusive mass distributions of protons, deuterons, and nuclei of ^{3}H (triton), ^{3}He and ^{4}He were investigated. The line shapes of mass distributions are described with the modified Crystal Ball functions in bins of rapidity, transverse momentum, and azimuthal angle of measured particles. Two examples of such studies are presented in Figure 39 for different transverse momentum ranges. The so obtained line shapes are then used to compute probabilities for each measurement in an event of being a given particle type. These probabilities are further used in the Identity Method to reconstruct cumulants of particle number distributions, including protons and light nuclei, as well as correlations between them. In addition, different methods for correcting tracking and particle selection inefficiencies are studied [3-5].

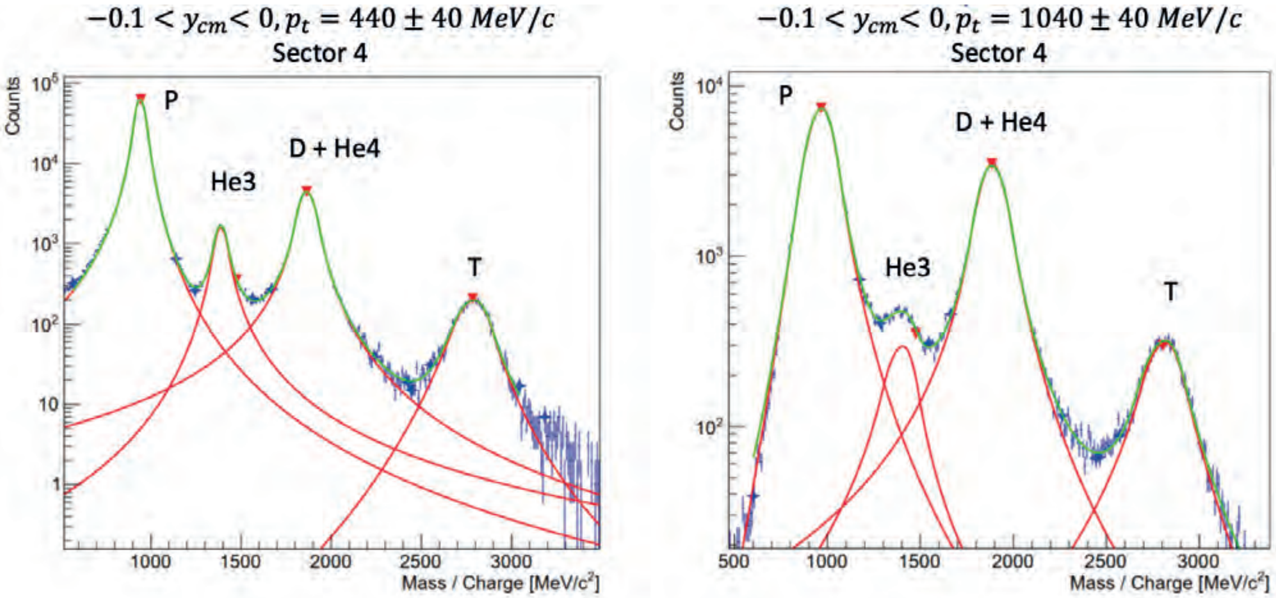

Figure 39. **Inclusive mass distributions of p, ^{3}He, ^{4}He, t obtained from Ag+Ag collisions at beam kinetic energy of 1.58A GeV, recorded by the HADES detector, and their functional description with the modified Crystal ball functions. These line shapes are later used in the Identity Method to reconstruct cumulants of multiplicity distributions of these particles. The distributions in the two panel are recorded in two different phase space bins as indicated in the head line of the plots.**

Integration of the KF-Particle Finder package to the HADES analysis framework

To potentially increase the performance in the reconstruction of weakly decaying particles in HADES, the KF particle package, developed originally for CBM and meanwhile used in the event reconstruction for various high energy heavy-ion experiments including STAR and ALICE, has been implemented in the HADES data analysis framework HYDRA. HADES is particular with respect to the arrangement of the tracking detectors as it features a field free region round the target in which the RICH is installed. The distance from target (primary vertex) to the first tracking planar tracking detector amounts to 40 to 80 cm for polar angles of 20 to 80 degrees, respectively. Particles carrying strangeness, i.e. neutral Kaons, Lambdas and hypernuclei have a decay vertex in the radiator volume of the RICH. The daughter particles traverse the RICH mirror and the shell of the radiator vessel before they enter the tracking stations and the magnetic field region. Momentum determination is not affected by multiple scattering in the RICH but in the extrapolation of the reconstructed charged tracks into the region of the RICH the effect of the material (energy loss and multiple scattering) has to be taken into account. This is achieved by applying Kalman filtering for track candidates and by extrapolating the track model backward towards the target region. The track extrapolator takes into account the residual magnetic field of the toroid and adds the multiple scattering in the RICH mirror, its shell and an installed δ electron shield as process noise. The beneficial feature of the KF Particle package is to add two additional constraints to the Kalman procedure, namely the common secondary vertex of the reconstructed particle tracks, combined to the group of daughter particles, as well as the requirement that the mother particle has been emitted from the known primary vertex [S. Gorbunov, PhD thesis, Goethe University Frankfurt, 2013]. For the latter, a straight track between the known primary vertex and the reconstructed secondary vertex is assumed and the primary vertex is taken as an additional measurement with zero error. As a result of applying the KF Particle filter method, the position of the secondary vertex is modified within the boundaries defined by the covariance matrix. In addition, a respective correction of the reconstructed tracks of the daughter particles can be calculated while obeying energy and momentum conservation at the secondary vertex.

Outlook for 2024

We are looking forward to the Au+Au energy scan run scheduled for March. The goal is to search for signs of criticality and to extend the excitation function of dilepton and strangeness production down to lower collision energies. We are also planning to replace the more than 20 years old front-end electronics of the drift chambers. The new boards feature the PASTTRECK amplifier-discriminator chip developed for the straw tracker of PANDA and time digitization with FPGAs. The system is compatible with the HADES TRB readout protocol. A bit more ahead is the preparation for pion beam experiments for which we try to evaluate if longer runs might be possible in conjunction with the commissioning of the new accelerator facility.

Selected publications of 2023

- [1] HADES Collaboration, R. Abou Yassine et al.: First measurement of massive virtual photon emission from N^* baryon resonances. Accepted by Phys. Rev. Lett.; e-Print: 2205.15914 [nucl-ex]
- [2] HADES Collaboration, R. Abou Yassine et al.: Inclusive e^+e^- production in collisions of pions with protons and nuclei in the second resonance region of baryons. e-Print: 2309.13357 [nucl-ex]
- [3] HADES Collaboration, R. Abou Yassine et al.: Investigation of the Σ^0 Production Mechanism in p (3.5 GeV) + p Collisions. Published in: Eur.Phys.J.A 60 (2024) 1, 18; e-Print: 2301.11766 [nucl-ex]; DOI:10.1140/epja/s10050-023-01214-1
- [4] HADES Collaboration, R. Abou Yassine et al.: Production of hydrogen isotopes and charged pions in p (3.5 GeV) + Nb93 reactions. Published in: Phys.Rev.C 108 (2023) 6, 064902; e-Print: 2301.06466 [nucl-ex]; DOI:10.1103/PhysRevC.108.064902 (publication)

4. Research of the NUSTAR Departments

Coordination: Prof. Dr. Christoph Scheidenberger Scheidenberger
(GSI & Justus-Liebig-Universität Gießen)
Authors: Thomas Aumann, Michael Block, Christoph E. Düllmann, Magdalena Górska, Christoph Scheidenberger

The NUSTAR Collaboration aims at experimental and theoretical exploration of nuclear physics and nuclear astrophysics with isotopes far off stability ranging from light to superheavy elements at GSI and FAIR. The corresponding departments at GSI and HIM are an integral part of the collaboration and contribute, often in a leading position. The process to identify key topics of and contributions to the NUSTAR scientific program within POF-5 ("Helmholtz Program-Orientend-Funding period no.5") and align them with the activities of the NUSTAR Collaboration overall was launched in 2023.

The NUSTAR Annual Meeting 2023 took place at GSI in its usual format in spring, and so did the NUSTAR Week in fall, which was held in Bucharest (Romania). At both events, the NUSTAR collaborators presented their results from the FAIR Phase-0 program and future perspectives and highlighted their plans for the first experiments at the main branch of the Super-FRS.

Although there was no physics beamtime available at GSI in 2023, the FAIR Phase-0 experiments of previous years have already led to many new findings and high-level publications; the data analysis is ongoing and will lead to even more scientific results. The FAIR Phase-0 program assures to maintain the high-level skills of the experiment teams, their expertise and capability to run complex experiments, and it is an indis-pensable asset for training and education of next-generation scientists. Such competences are particularly important to prepare the experiments at FAIR and to continue superheavy element research at GSI. An important step for the latter field was the successful commissioning of the first cryomodule of the new super-conducting cw linear accelerator HELIAC, which opens up new long-term perspectives for superheavy element research on the world-class level. An engineering run at the end of the year gave the opportunity to prepare the major research instruments and detector systems of the NUSTAR collaboration SHIP/SHIPTRAP, TASCA, FRS/FRS Ion Catcher, DESPEC, and R3B for the physics runs in 2024.

4.1 FRS/SFRS

Head: Prof. Dr. Christoph Scheidenberger (JLU Gießen & GSI)
Authors: Timo Dickel, Hans Geissel, Emma Haettner, Christine Hornung, Oleg Kiselev, Kenta Itahashi, Daria Kostyleva, Ivan Mukha, Wolfgang Plaß, Sivaji Purushothaman, Take Saito, Christoph Scheidenberger, Yoshiki Tanaka

The Super-FRS Experiment Collaboration runs pilot experiments at the FRS and prepares for FAIR Early-Science and First-Science experiments at the Super-FRS. The common feature are specific ion-optical modes of both instruments in combination with ancillary detectors for a variety of nuclear physics experiments with exotic nuclei including applications. The department "FRS/SFRS Experiments" is integral part of the collaboration and contributes with simulations, detector developments, experiments and data analysis.

Tests and experiments performed in 2023

The FRS group participated in the engineering run in fall 2023 and commissioned the standard equipment of the FRS (i.e. that is needed for production, separation and identification of exotic nuclei, including simulations, data acquisition system and online analysis software) for all the NUSTAR and APPA experiments with relativistic radioactive beams, which are scheduled for the first half of 2024. As an important asset, the MBS data acquisition system was modified such that the rate capability could be increased to approximately 300%.

Detector developments for EXPERT: experimental studies of proton-unbound light nuclei via in-flight decay spectroscopy at the FRS

Figure 40. Setup for test of microstrip detectors with IR laser.

The charged-particle tracking-system on the basis of silicon-microstrip and pixel detectors (FOOT, ALPIDE) has been further developed and tested offline and online in close collaboration with the R3B department. Six new, large-area microstrip detectors with corresponding FPGA-based readout electronics and improved software were integrated in the GSI DAQ system. Extensive tests were performed at GSI with a dedicated IR laser (see Figure 40). The tests helped to evaluate the maximum rate capability and to calibrate the detector response and simulate the energy deposit of medium-heavy ions, which are considered for forthcoming experiments at FRS and Super-FRS. The microstrip detectors were tested together with pixel detectors in summer 2023 in a dedicated experiment at COSY at FZ Jülich. A proton beam at different intensities and energies was used for the determination of position resolution and efficiency. Several GADAST crystals, which will also form a part of the EXPERT setup, have been tested for the first time with proton beams in the same experiment.

For the experiments scheduled at the FRS main branch in 2024 and 2025, a new scattering chamber was designed (see Figure 41) and manufactured by Silesian University (Opava) and Warsaw University. Together with the electronics and software for pixel detectors and the newly developed mounting concept, a new, dedicated large-area tracking setup has been almost completed.

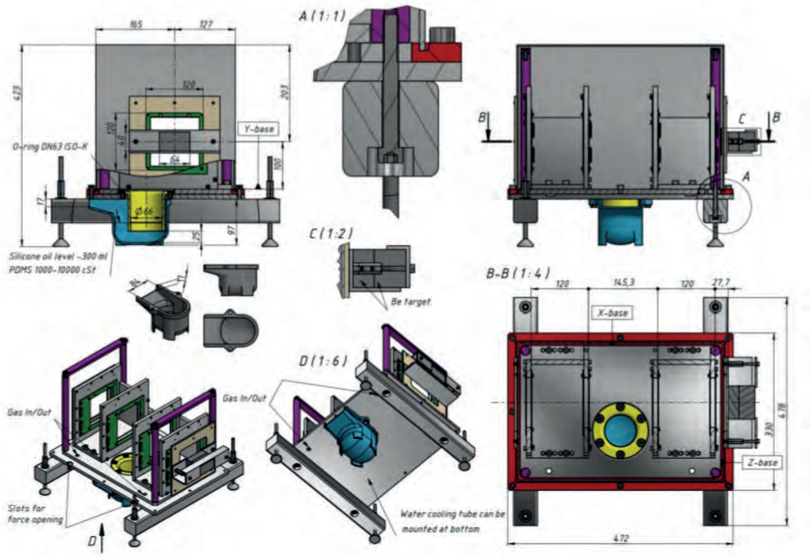

Figure 41. Design of the scattering chamber for the tracking system.

Production of radioactive molecules at the FRS Ion Catcher: a proof of principle for future studies

Molecules serve as captivating laboratories for probing fundamental physics, offering unique insights into phenomena such as the electric dipole moment of the electron (eEDM). What makes molecules particularly intriguing for such experiments is their much stronger electric fields than other methods, reaching magnitudes of gigavolts per centimeter (GV/cm). This heightened sensitivity to electric fields enables more precise measurements of the eEDM, and recent experiments utilizing molecules like YbF or HfF have produced the most stringent limits on the eEDM. However, to conduct even most precise experiments, specific requirements must be met: (i) high atomic number (Z), (ii) high polarizability, (iii) correct electron configuration, and (iv) their applicability to laser cooling. These criteria favor the use of actinide elements, which, however, exist exclusively radioactive isotopes. Consequently, methodologies need to be developed to produce, characterize and study molecules containing these radioactive species, understanding and identifying the most promising candidates for eEDM testing.

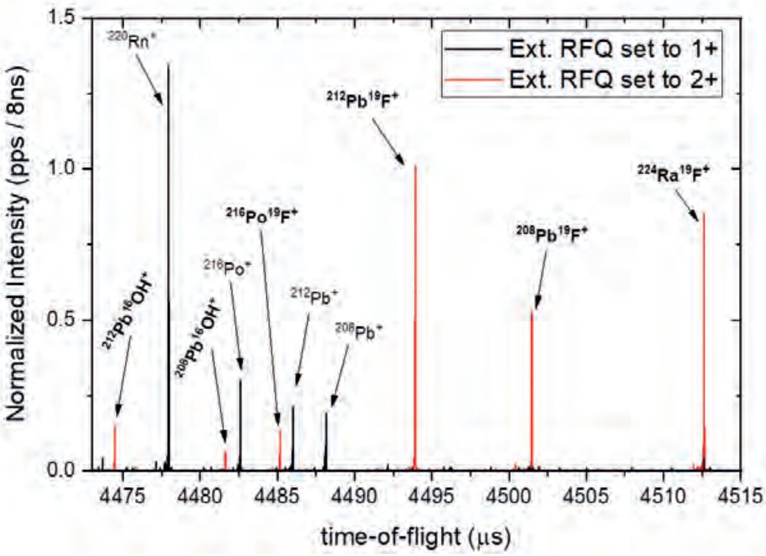

Figure 42. Time-of-flight spectrum measured at the FRS Ion Catcher showing various reaction products of actinides with SF_6 gas.

In December 2023, a test experiment was conducted at the FRS Ion Catcher to produce various radioactive molecules. Lead (Pb), polonium (Po), and radium (Ra) ions from an internal offline source were prepared for this purpose and reacted with SF_6-gas in a segment of the RFQ beamline. The resulting reaction products were identified, analyzed and quantified using the MR-TOF-MS. Figure 42 shows a mass spectrum obtained, showcasing measurements for both singly and doubly charged species before entering the reaction chamber. This method demonstrates its efficacy by enabling the study of multiple reaction channels (i.e., charge states and reaction partners) across various elements within a single experiment, facilitating the quantification and identification of all reaction products.

Results from previous FAIR Phase-0 experiments

Results from direct mass measurements near ^{100}Sn

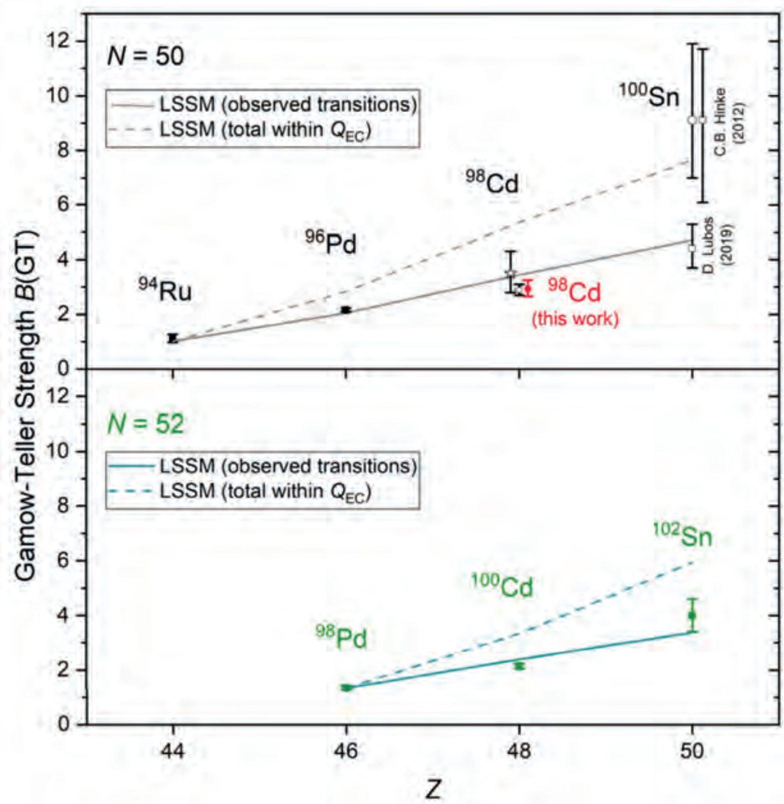

Figure 43. The Gamow-Teller strength B_{GT} for 0^+->1^+ transitions for even-even N=50 isotones (top panel) and N=52 isotones (bottom panel). The BGT values have been calculated based on the latest information from the Nuclear Data Sheets. The black star and the black triangle at Z=48 show previously reported values for ^{98}Cd based on an indirect mass measurement. The red circle shows the new B_{GT} value calculated based on the first direct mass measurement (this work) and all the recent information. The open squares show the B_{GT} values for ^{100}Sn reported in [2] and [3]. The LSSM calculations are shown with the solid line with the GT strength summed for the experimentally observed decaying states, and with dashed line for the total strength contained in the QEC window.

Direct mass measurements of neutron-deficient nuclides around the N=50 shell closure below ^{100}Sn, produced by projectile fragmentation of ^{124}Xe, were performed at the FRS Ion Catcher. Fourteen ground states and two isomers were measured with relative mass uncertainties down to $1\cdot10^{-7}$ using the multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) of the FRS Ion Catcher, including the first direct mass measurements of ^{98}Cd and ^{97}Rh [1]. A new value of QEC = 5437±67 keV was obtained for ^{98}Cd, resulting in a summed Gamow-Teller (GT) strength for the five observed transitions 0^+->1^+ of $B_{GT}=2.94^{+0.32}_{-0.28}$. A systematic comparison of experimental and theoretical BGT values for even-even isotones at N=50 and N=52 was performed (Figure 43). Large-scale shell-model (LSSM) calculations, performed for the entire BGT strength possible to observe in β-decay, as well as only for the experimentally known transitions, enable, for the first time, a direct comparison between theory and experiment. The experimental and theoretical value are in perfect agreement. With these new values, the apparent controversy of the QEC values for ^{100}Sn [2-4] was investigated with two different observables, namely the shifted two-neutron shell gap Δ_{2n}(Z,N+2) and the Gamow-Teller strength B_{GT}. For Δ_{2n}(Z,N+2), the previously known trends have been confirmed; following the arguments laid out in [4], the QEC value reported by Hinke et al. is supported [2]. The systematic investigation of the B_{GT} values, however, clearly supports the QEC value reported by Lubos et al. [3]. Therefore, the current situation calls for new and improved experiments.

Basic studies using positron emitters for possible future ion-beam therapy

Fast and reliable monitoring is crucial for maximizing the benefits of therapeutic ion beams like carbon and oxygen while minimizing damage to healthy tissue due to range uncertainties. Quasi-real-time range monitoring using in-beam positron emission tomography (PET) with therapeutic beams of positron-emitters of carbon and oxygen offers a promising approach. A quantitative and qualitative comparison of the therapy-relevant beams of positron-emitting isotopes of carbon and oxygen within the context of quasi-real-time range verification capability [5,6] was carried out at the FRS. Figure 44 a shows the evolution of the 1D positron activity peak position as a function of the total number of implanted ions. The actual number of implanted ions and observation time required for a range verification depends on the geometry and sensitivity of the scanners. From an instrumental perspective, the slower decay rate of long-lived positron emitters compared to short-lived ones can be compensated by higher intensity. However, for therapeutic applications it is advantageous to achieve range verification “in situ” as quick as possible with the smallest possible dose.

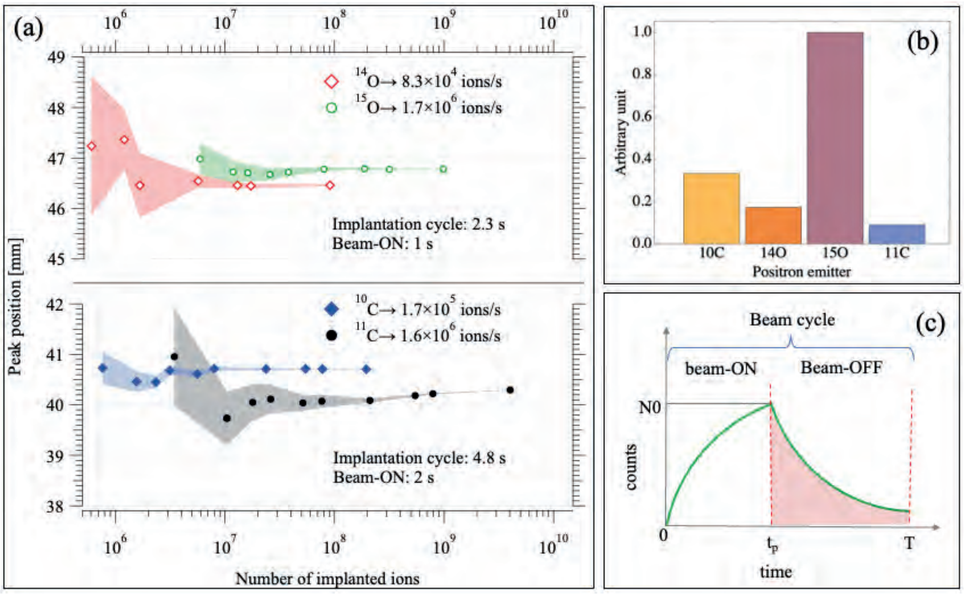

Figure 44. a) Evolution of the 1D positron activity peak position as a function of the total number of implanted ions, during high and low-energy implantation of ^{15}O, ^{14}O [6] and ^{11}C, ^{10}C [5]. The average beam intensity used during the implantation is indicated in the legend. The shaded region represents the statistical uncertainties. Data with a deviation of ≥±0.75 mm from the asymptotic value or with statistical uncertainty 0.75 mm are indicated by filled gray circles. b) Calculated yields of coincidence events of ^{10}C, ^{14}O, ^{15}O and ^{11}C normalized to the yield of ^{15}O, for the assumption of a beam on for 1s followed by beam off for 1.5s. Production cross sections from [7], assuming same primary beam intensity of ^{12}C and ^{16}O. c) Schematic time diagram.

In the context of quasi-real-time in-beam PET, the number of implanted ions (which translates directly proportional to the dose deposition) and the time required for adequate range verification from the start of the implantation are the decisive factors for choosing a candidate. Figure 44 b compares positron emitters in quasi-real-time in-beam PET, illustrating the impact of half-life and intensity on image quality.

The figure displays the calculated yields of coincidence events for ^{10}C, ^{14}O, ^{15}O, and ^{11}C normalized to the yield of ^{15}O, assuming the beam is ON for 1 second followed by being OFF for 1.5 seconds. The production cross-sections are taken from [7], with the assumption of the same primary beam intensity of ^{12}C and ^{16}O. Only the coincidence events recorded during the beam OFF intervals (see Figure 44 c) are considered to avoid contributions from prompt gammas and short-lived positron emitters produced by nuclear fragmentation.

In terms of the half-live, ^{10}C is the best candidate for quasi-real-time range monitoring. However, the production cross-section of ^{10}C is an order of magnitude lower than that of ^{11}C and ^{15}O. This implies that the production of ^{10}C requires an order of magnitude higher intensity from the driver accelerator to reach therapeutic intensities compared to ^{11}C and ^{15}O. In the case of ^{11}C, its half-life of 1221.8 s makes it not optimal for quasi-real-time range monitoring using in-beam PET. From the performed measurements (see results in Figure 44 b), ^{15}O comes out as a clear favorite among all considered isotopes for quasi-real-time range monitoring by in-beam PET during therapy as quantified in the figure of merit analysis. The results demonstrate that, from the perspective of an in-flight production and separation method, ^{15}O is the better choice in terms of achievable intensity and fast imaging. In conclusion, ^{15}O is the most technically feasible choice for a therapeutic beam that allows quasi-real-time range monitoring by in-beam PET due to its faster response at a lower dose. The study could also demonstrate the feasibility of producing ^{15}O beams with an intensity, purity, and energy suitable for ion-beam therapy using the method of ^{16}O-projectile fragmentation and in-flight separation.

Data analysis from experiments using WASA@FRS:

The analysis of data taken in 2022 with WASA@FRS are ongoing. For hypernuclear studies [8,9], the basic framework of a machine learning model, here employing Graph Neural Network (GNN) methods, has been set up. Its performance has been studied with Monte Carlo simulation data [10]. It has been integrated in the analysis package for complete trace reconstruction using Kalman Filter track fitting for both, experimental and simulated data, and is presently used for the final tuning of data analysis parameters. Also the data analysis of the search for eta'-mesic nuclei progresses steadily. The measured inclusive 12C(p,d) excitation spectrum near the eta' emission threshold shows good agreement with that of the previous experiment. The particle identification capability of WASA is found to be high enough to set cut conditions on the final states of the reaction products. The momentum analysis of WASA@FRS is presently being refined.

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- [10] H. Ekawa, et al., EPJ A59, 103 (2023).

Outlook to 2024

The data analysis of experiments performed in FAIR Phase-0 in the framework of the Super-FRS Experiment Collaboration and the publication of results will continue. Also the construction, test and debugging of detectors, methods and algorithms for Early-Science and First-Science experiments will continue and steadily be accompanied by simulations. Experiments with novel setups studying MNT reactions at UNILAC energies will be performed at X6 and with slowed-down uranium beams at the FRS. Further FRS experiments aim at the measurement of production cross sections of neutron-deficient projectile fragments of uranium and the investigation of fission isomers; both activities aim at providing reliable yield estimates for new proposals at the Super-FRS.

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- E. Haettner, H. Geissel, B. Franczak, D. Kostyleva, S. Purushothaman, Y.K. Tanaka, et al., “Production and separation of positron emitters for hadron therapy at FRS-Cave M” Nucl. Instr. Meth. Res. 541, 114-116 (2023)
- D. Kostyleva, S. Purushothaman, P. Dendooven, E. Haettner, et al., “Precision of the PET activity range during irradiation with ^{10}C, ^{11}C, and ^{12}C beams” Phys. Med. Biol. 68, 015004 (2023)
- A. Mollaebrahimi, C. Hornung, T. Dickel, D. Amanbayev, G. Kripko-Koncz, et al., “Studying Gamow-Teller transitions and the assignment of isomeric and ground states at N=50” Phys. Lett. B839, 137833 (2023)
- S. Purushothaman, D. Kostyleva, P. Dendooven, E. Haettner, et al., “Quasi-real-time range monitoring by in-beam PET: a case for ^{15}O“ Sci. Rep. 13, 18788 (2023)
- T.R. Saito, et al.,“The WASA-FRS project at GSI and its perspective” Nucl. Instr. Meth. Phys. Res. B542, 22-25 (2023)

4.2 Nuclear reactions

Head: Prof. Dr. Thomas Aumann (TU Darmstadt & GSI)
Author: Thomas Aumann

The department Nuclear Reactions develops and operates the R^{3}B (Reactions with Relativistic Radioactive Beams) experiment, which allows for kinematically complete measurements of reactions with heavy-ion beams with typical energies of 0.5 to 1 GeV/nucleon. The scientific aim is to determine and understand the properties of neutron-proton asymmetric nuclei and nuclear matter, the properties of astrophysical objects like neutron stars, as well as nucleosynthesis processes in stars, star explosions, and neutron-star mergers by measurements of reactions with short-lived nuclei. A start version of the FAIR 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 2024, the setup has been further completed during 2023 with an upgrade of the CALIFA calorimeter with detectors at the very forward angles, a re-configuration of the silicon vertex tracker including new ALPIDE detectors, as well as a refurbishment of the time-of-flight wall and further construction of NeuLAND.

Highlights in 2023

First observation of ^{28}O

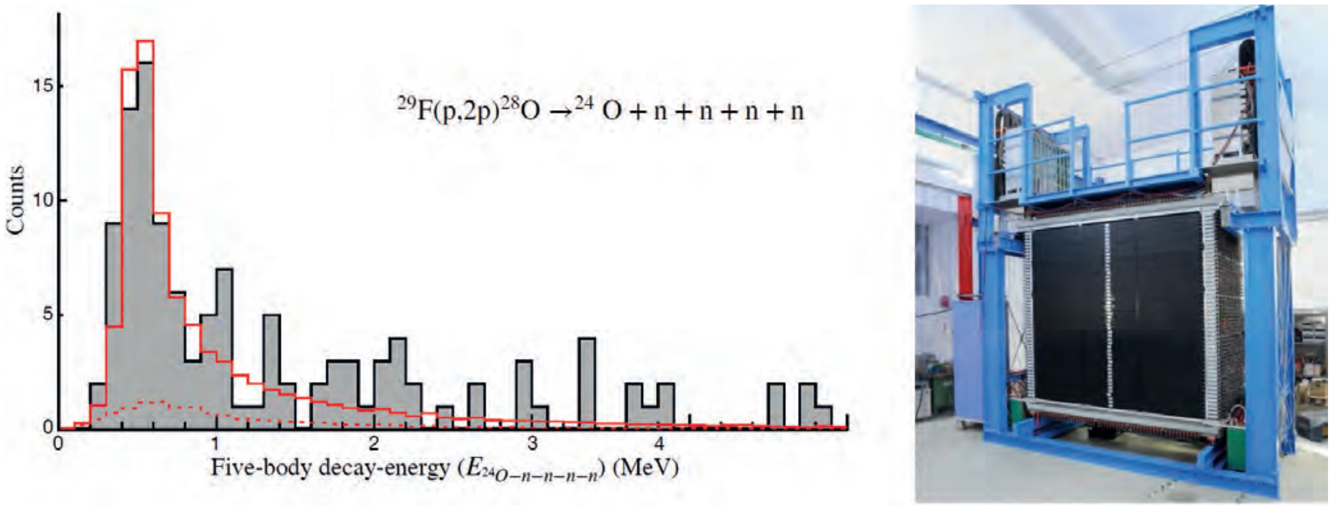

Figure 45. **Left: Invariant-mass spectrum of the five-body decay of ^{28}O into ^{24}O plus four neutrons reconstructed from a kinematically complete measurement of the decay with the R3B NeuLAND and NEBULA neutron detectors at SAMURAI at the RIBF [1]. Right: Photograph of the R3B NeuLAND detector at Cave C at GSI.**

The exploration of the neutron dripline is one of the most active areas in the research of rare isotopes with extreme neutron-to-proton imbalances. While experimentally extremely challenging, the structure of such nuclei provides stringent tests of nuclear theory including since recent years ab initio approaches based on interactions constructed from first principles. The knowledge on the limits of stability, the neutron dripline, is limited to the light nuclei and was only recently extended form oxygen to neon by experiments at RIKEN. We report here on the first observation of ^{28}O, which is four neutrons beyond the dripline located at ^{24}O. With its proton and neutron numbers Z=8 and N=20, ^{28}O was anticipated to be the most neutron-rich doubly-magic nucleus reachable in the laboratory.

The experimental challenges are the production and the identification and spectroscopy of ^{28}O by a kinematically complete measurement of its five-body decay into ^{24}O plus four neutrons. This experiment was the first succeeding in invariant-mass spectroscopy with four neutrons in the final state, thanks to the addition of the R^{3}B NeuLAND detector to the NEBULA detector at the SAMURAI setup at RIKEN. The resulting energy spectrum of the five-body decay [1] is shown on the left in Figure 45. The pronounced peak at around 500 keV corresponds to the ground-state energy of ^{28}O relative to ^{24}O. No statistically significant indication for the population of excited states are visible.

Besides the energy of the ground-state resonance of 0.46(5) MeV, the decay pattern of ^{28}O could be studied, the ^{27}O resonance was observed for first time, as well as the production cross section for ^{28}O from ^{29}F could be measured. From the results and the comparison to theoretical modellings it is concluded, that ^{28}O is not as expected a doubly-magic nucleus, i.e., that the N=20 neutron shell is not closed but that the neutron configuration is similarly as for the neutron-rich fluorine isotopes dominated by intruder configurations.

The ^{28}O nucleus has been produced in a ^{29}F(p,2p)^{28}O quasi-free knockout reaction at the SAMURAI setup at the RIBF. The secondary beam ^{29}F has been prepared with 235 MeV/nucleon by the BIGRIPS separator at RIKEN Nishina center with a typical rate of 90 pps from a primary ^{48}Ca beam at 345 MeV/nucleon and with an intensity of 3x10^{12} pps. The cross section to produce ^{28}O from ^{29}F was measured with 1.4(2) mb. A major challenge was the four-neutron detection in terms of efficiency and cross-talk rejection, which is necessary to obtain a unique detection of the four neutrons in coincidence and to measure their momenta. This has been achieved by using a two-wall configuration with the R^{3}B NeuLAND and NEBULA arrays separated with a flight distance between them. A first demonstrator detector of NeuLAND consisting of four double planes at that time was shipped to Japan and prepared for the experiment. With this combination, the collaboration succeeded in the first measurement of high-resolution invariant-mass spectroscopy with four neutrons in coincidence in a radioactive-beam experiment. The NeuLAND detector is since then and still is continuously being further constructed in order to reach best-possible conditions for detection of multi-neutron events at R^{3}B at FAIR.

First elastic proton scattering with a radioactive beam in a storage ring

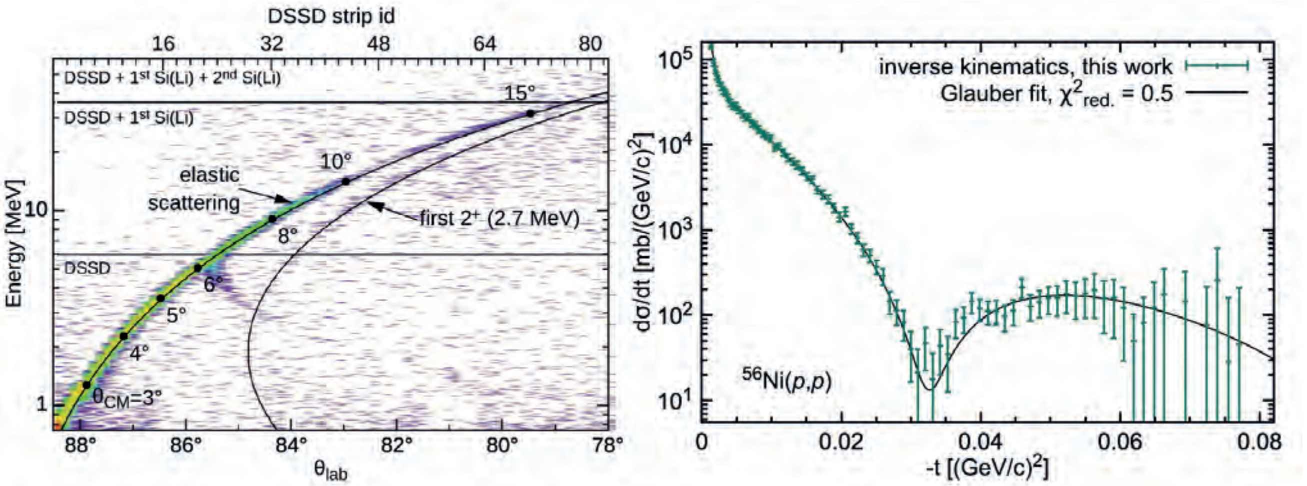

Figure 46. Left: Reconstructed energy of the scattered protons from the energy deposits measured with the individual detectors of the detector telescope as a function of the scattering angle θ_{lab}. Calculated kinematical curves for both elastic and inelastic scattering to the first- excited state of ^{56}Ni are overlaid. Right: Differential cross section for elastic proton scattering off ^{56}Ni as a function of the momentum transfer. The result of the analyzis in a Glauber calculation is overlaid as solid curve.

Nuclear radii and density distributions are among masses the first observables to be compared to test nuclear theory. If the charge distribution is known from electron scattering or laser spectroscopy, also the neutron distribution and its radius can be determined by a measurement of proton elastic scattering. The storage ring has the advantage to enable precise measurements at low momentum transfer, where the energy of the recoiling proton is small, which needs thin targets. Here the combination of a gas-jet target and the circulation in the storage ring is advantageous. The EXL collaboration measured now for the first time the elastic proton scattering in the ESR storage ring for the doubly-magic short-lived nucleus ^{56}Ni at 390 MeV/nucleon [2].

The recontsructed energy of the scattered protons as a function of the laboraty scattering angle is shwn in the left frame of Figure 46. The elastic scattering is well separated from the first 2$^+$ state due to the excellent resolution. The differential elastic cross section is shown in the right frame of Figure 46 as a function of the momentum transfer-t. The covered momentum tranfer includes the first diffraction minimum as well as the following maximun which contains the information on radius and diffuseness of the matter distribution. The data were analyzed with the Glauber multiple-sacttering theory with a two-parameter Fermi distribution for the matter density as input, yielding radius and diffuseness of 3.74(6) fm and 0.59(4) fm, repectively. This method developed at the ESR can be later used at FAIR for more exotic and heavier nuclei as soon as pre-coolded radioactive beams will be available from the collectror ring.

Outlook for 2024

The R^{3}B collaboration has started in 2022 a program to study short-range correlations (SRC) with radioactive neutron-rich nuclei with an experiment on ^{12}C and ^{16}C. The quasi-free (p,2p) knockout reaction has been used to knockout a proton from the SRC pair, which causes the correlated 2nd nucleon to leave the nucleus as well. The inverse kinematics allow the detection of all particles including the residual fragment, the knocked as well as the recoiling nucleon, and thus an investigation of SRC properties in neutron-proton asymmetric nuclei. A complementary experimental method is the knockout of the correlated deuteron-like pair in a (p,pd) quasi-elastic scattering. A first experiment of this type is being prepared to run in 2024.

Selected publications of 2023

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4.3 Nuclear spectroscopy

Head: Dr. Magdalena Górska

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

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

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

Highlights in 2023

Effective charge determination in ^{130}Cd: the two-proton-hole nucleus in ^{132}Sn

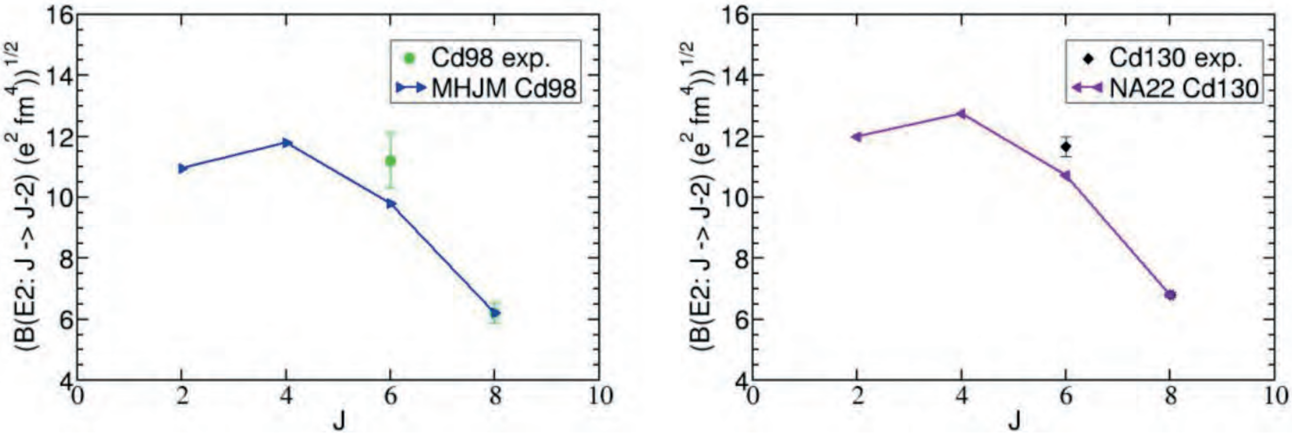

Figure 47. Reduced transition probabilities for the isomeric decay in the two-proton-holes nuclei ^{98,130}Cd with respect to ^{100,132}Sn doubly magic core, respectively. The calculations are based on realistic interaction adopted to the nuclei of each of the regions at GSI.

An interpretation of 12-year-old experimental data collected at RIFB RIKEN in Japan was performed focusing on the 8^+ isomeric decay in ^{130}Cd, with superior statistics as compared to a previous measurement at GSI. The rich data allowed the extraction of the not only the 8^+ lifetime with improved accuracy, but also the 6^+ state lifetime for the first time. Based on this result, the transition strength could be extracted for the decays of each of the two states belonging to the same seniority ν=2 cascade. The results, submitted for publication [1], are shown in Figure 47 in comparison to the NA22 shell model calculations, employing the newly-adopted single particle/hole energies known around ^{132}Sn. Based on the pure proton $g_{9/2}^{-2}$ configuration of these states in ^{130}Cd, an effective proton charge could be extracted from this decay similarly as it was already done for ^{98}Cd [2]. While the isospin dependence of effective charges is discussed in the forthcoming publication in a larger configuration space, in Figure 47 it is shown that the transition rate for 6^+ states decay cannot be reproduced in either of the two nuclei when the effective charge is extracted based on the 8^+ state decay strength. The difference is more pronounced for ^{130}Cd because of higher experimental precision. There is no explanation to that puzzle at present.

Isospin symmetry in the T = 1, A = 62 triplet

Recently, a paper discussing the isospin symmetry in the T = 1, A = 62 triplet has been published in Physics Letters B [3]. The study presents a combination of in-beam γ-ray spectroscopy experiments done at the RIBF with projectile fragmentation and at JYFL-ACCLAB using a fusion-evaporation reaction. The first excited states in ^{62}Ga and ^{62}Ge were identified, resolving discrepant interpretations in the literature. In comparison with shell-model calculations, the mirror energy differences confirm that the radius of the p-orbitals shrink when occupied by at least one nucleon on average.

artEmis Project

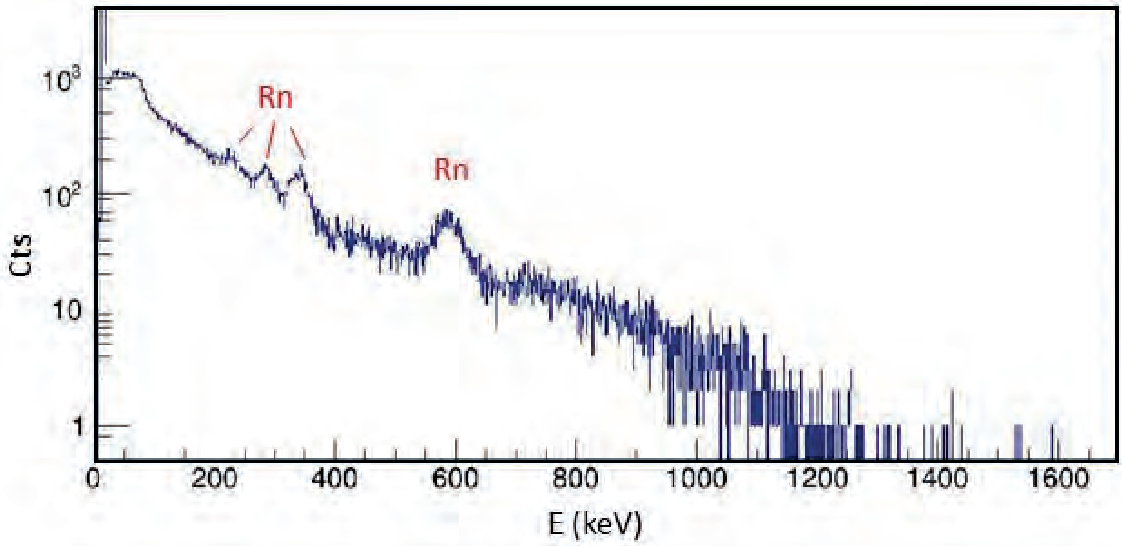

Figure 48. Characteristic γ-ray spectrum of Rn decays in water, measured at the SURO institute, Prague.

The artEmis project deals with an earthquake early-warning sensor network, based on sophisticated groundwater measurements. In a novel approach, the radon concentration of the water is measured, as well as additional physical parameters like temperature, pressure and acidity. The aim is to deploy hundreds of sensor units in groundwater wells and springs covering earthquake prone areas. Initially, areas on the Ionian Islands in Greece, the Abruzzi Mountains in Italy, and in the Swiss Alps will be equipped. In this international EU-funded project, our KSP team is responsible for the development and realization of the sensor units. A series of six demonstrator units have been built and tested so far. A CsI(Tl) scintillator read out by SiPM and digitized by time-over-threshold forms the heart of the sensor head. Figure 48 shows the response of this gamma detector to radon-loaded (10 Bq/l) water. For this measurement, the sensor head has been placed at the centre of a 1000 l plastic tank filled with water. It is interesting to note that the four characteristic gamma lines from the Rn daughter decay at 242, 295, 352, and 609 keV are strongly reduced due to multiple Compton scattering in the large water volume. On the other hand, environmental gamma rays from outside the water volume, like ^{40}K are strongly shielded. Indeed >90% of the measured gamma intensity is due to Rn decays. Radon transport in groundwater is assumed to be associated with a carrier gas, i.e. CO_2. The CO_2 concentration can be obtained by measuring the acidity of the water. A few days before an earthquake, the Rn yield in groundwater may change. If this change is correlated with the acidity of the water, there is strong evidence for a pre-cursor signal. Water pressure changes like shock waves, measured with gyroscopes, or even sound waves, measured with sensitive underwater microphones will provide additional earthquake information. Artificial Intelligence and Machine Learning methods will be used for real-time analysis of the many data produced by the sensor units.

LNL experiment: Spectroscopy and lifetime measurements toward the Island of Inversion

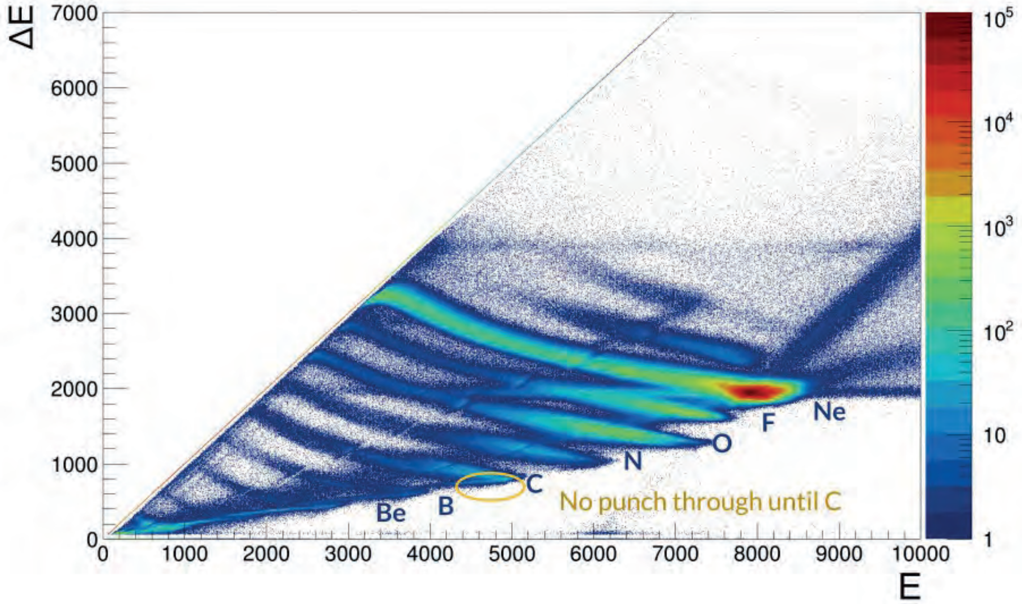

Figure 49. Particle identification plot for light ions detected in PRISMA. The energy loss in an ionization chamber versus the total kinetic energy detected is allowing for clear separation of the different elements.

An experiment to study the evolution of nuclear structure towards the N = 20 Island of Inversion lead by KSP has been performed in April 2023 at Legnaro National Laboratory [4]. In this experiment, a light ^{22}Ne beam irradiated ^{238}U targets (fabricated by GSI target laboratory) to populate neutron-rich Ne and O isotopes by multi-nucleon transfer reactions. The goal was to measure excited state lifetimes employing the AGATA γ-ray tracking detector array. In this pilot experiment, the main focus was to optimize the PRISMA spectrometer for use with light ions which was successfully accomplished as shown in the particle identification plot in Figure 49. A new method of mass identification has also been established allowing the recovery of events where, due to low efficiency, the position sensitive PPAC detectors did not detect any particle.

EUROLABS activities

There are activities led by the KSP at GSI in relation to the development and advancement of remote access to the EURO-LABS facilities within the Service Improvements sub-task of the EURO-LABS work package for Nuclear Physics (WP2.5.C1). In this context, remote access is defined as any kind of accessibility to experimental operation from outside of experimental areas (i.e. for use by local and external experts) in order to maximise beam-on-target and scientific output. Along with three partner institutions (UMCG, INFN Milano and IFIN-HH), the goal of the activities is to provide a user-friendly database of remote-access tools to the EURO-LABS community, develop and implement new tools at the partner institutions and provide training opportunities. A survey was carried out in early 2023 to learn the current status of remote access across the EURO-LABS consortium and to collect the requirements and needs. The results of the survey guide the technical strategy for further tool development. The database, which contains comprehensive information about the tools available within the community, how to use them and who to contact for help with implementation, will be available by the end of February 2024.

The INTRANS (Instrumentation and Training for Nuclear Spectroscopy and Reaction Dynamics) sub-task of EURO-LABS (WP2.5.C5) takes the challenge of providing an expertise on an optimal employment of experimental setups in EURO-LABS for nuclear spectroscopy and nuclear reactions communities. It is led by the KSP department and concentrates on the organization of training activities and schools related to traveling detectors in Europe. In particular, an analysis school was organized at Legnaro National Laboratory concerning data obtained with the AGATA HPGe array.

FAIR Phase-0: experiments

Proton-neutron interaction based on seniority remnant in ^{94}Pd

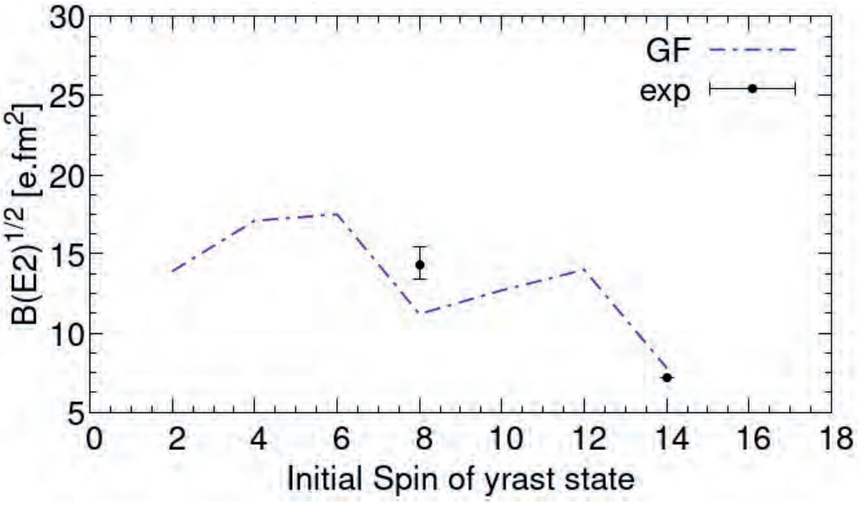

Figure 50. **Square root of the reduced transition probability of the decay of Yrast excited states in ^{94}Pd calculated with GF [5] (and references therein) interaction compared to the existing experimental data.**

The main goal of the first DESPEC experiment performed in March 2020 was the measurement of the transition strength of the 8$^+$ state decay in ^{94}Pd. A direct comparison between the predictions of various approaches of shell-model interactions and valence configuration spaces was made. Special interest concentrated on the treatment of the proton-neutron interaction for this $T_z = +1$ nucleus, intermediate between the N = Z line and the N = 50 closed neutron shell. More precisely, ^{94}Pd is the even-even neighbour of the difficult-to-access N=Z ^{92}Pd, ^{96}Cd and ^{94}Ag nuclei. The ^{94}Pd spectrum represents the T=1 partner of ^{94}Ag. With respect to seniority, it reflects with $\nu_\pi = 2, 4$, $\nu_\nu = 2$ the transition from $\nu_\pi = \nu_\nu = 2, 4$ ^{92}Pd to $\nu_\pi = \nu_\nu = 2$ ^{96}Cd with an intermediate B(E2; I -> I - 2) pattern in the $g_{9/2}$ orbital (for more details see Fig. 3 of Ref. [6]). The experimental result submitted for publication is presented in Figure 50 and compared to the empirical shell-model approach [5] and references therein. It is clearly seen that the good agreement observed for the known 14$^+$ state decay is not present for the newly-measured 8$^+$ state. This requires a more sophisticated approach as presently considered [7].

First results from LISA

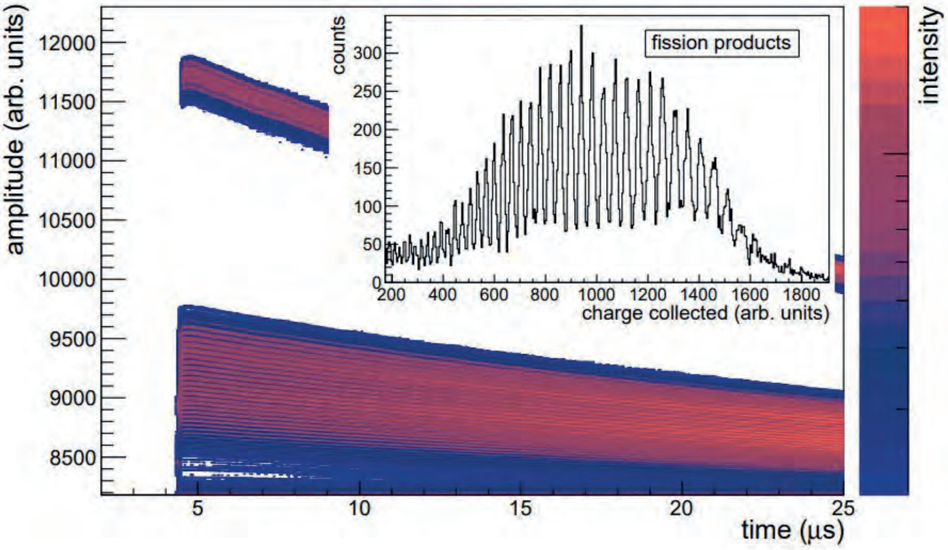

Figure 51. **Heavy beam-like fragments and fission products identified with a single crystalline diamond detector.**

During the 2023 the engineering runs at GSI, the first in-beam tests of LISA [8] detectors have been performed. A single diamond detector (named "Tokyo") was inserted at the S2 focal plane and tested with heavy ions. The beam conditions in a first run where a ^{14}N primary beam at 700 AMeV was used, were not favorable for the test purpose, resulting in a very small energy loss of the ions in the diamond and a reduced resolution. Nevertheless, it was possible to identify two neighboring elements and detect ^{13}N and ^{11}C in the beam. In a second test, a cocktail beam consisting of uranium beam fragments (proton number Z ~ 80−85) was delivered to the LISA test setup at the S2 focal area. Along with these beam fragments, also products of in-flight fission were transmitted. Figure 51 shows the wave forms recorded for wave forms recorded for particles impinging on the diamond detector. Beam fragments and fission products can be clearly separated, but also individual proton numbers can be distinguished by their characteristic energy loss or pulse height. The inset shows the pulse-height spectrum for the fission fragments, demonstrating the capability to separate different elements with the diamond detectors, a milestone of the project.

Outlook for 2024

The HISPEC/DESPEC collaboration is going to perform several experiments in 2024 at FAIR Phase-0. In particular, the rare-earth isotopes will be studied as fragmentation products of the ^{170}Er beam newly developed at GSI [9]. Further U fragmentation nuclear structure experiments are planned as a flagship of GSI/FAIR. Several test experiments are also planned at GSI in a secondary user mode, including test runs for LISA and a novel active fiber implanter, FIMP. In the beginning of 2024, six artEmis demonstrator sensor units will be deployed in earthquake-prone areas in Europe in order to gain experience. Later in that year another 30 further improved sensor units shall be built and distributed in selected groundwater sites. In view of only scarce beam time available at GSI at the moment, KSP plans to perform experiments elsewhere. In particular, an accepted and A-rated proposal for an experiment at RIBF is expected to lead the transition rate of the decay if the 8^+ state in ^{96}Cd [10]. This will relate to performed at GSI ^{94}Pd experiment and test effectively p-n interactions for this N=Z nucleus just below ^{100}Sn. The analysis of excited states from an in-beam experiment at RIBF is in ^{130}Cd is at its final stage. A follow-up experiment to focus on the physics case and determine lifetimes of intruder states near the Island of Inversion has been approved with grade A by the PAC in Legnaro [11].

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4.4 Superheavy elements at GSI and HI Mainz

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In 2023, there was no user beamtime served at GSI; activities at GSI therefore focused on the analysis and publication of data obtained previously, both at GSI as well as abroad, e.g., at ANU Canberra. Online chemistry studies were performed at NPI CAS Řež (CZ). Technical and method developments as well as offline work were performed at GSI and at HIM, for example for applications in laser spectroscopy, where a three-month campaign with the 20-h isotope ^{255}Fm obtained from a 40-d ^{255}Es generator system was employed to support two different studies: on the one hand this allowed complementing laser spectroscopy studies along a long isotopic Fm sequence by this neutron-rich isotope, and on the other hand it enabled fundamental studies in the life sciences. Technical developments to break current frontiers in future beamtimes to increase production rates, to advance to heavier, more exotic systems, to gain access to new observables and to provide higher-quality data were carried out.

Highlights in 2023

Synthesis / Nuclear Reactions

The heaviest superheavy elements (SHE) with atomic numbers Z=114-118 have been discovered in ^{48}Ca-induced fusion reactions with targets of Pu-Cf isotopes. Cross sections to form SHE in such fusion reactions decrease smoothly with increasing Z of the compound nucleus. The dynamical mechanisms underlying this trend are commonly attributed to an increase in the quasi-fission component acting prior to complete fusion. The quasi-fission outcomes from such reactions result in the emission of heavy fragments with masses around the doubly-magic lead, which have been studied at TASCA [A. Di Nitto et al., Phys. Lett. B 784, 199 (2018)] indicating the importance of the shell effect in the reaction dynamics. The origin of the effects of the ^{208}Pb shell closure was studied in collaborative work of the SHE Chemistry departments at GSI and HIM and the nuclear reactions group at the Australian National University (ANU), Canberra, Australia, at the Heavy Ion Accelerator Facility of ANU [1]. The ^{50}Ti projectile, most promising for the synthesis of elements beyond Og [J. Khuyagbaatar et al., Phys. Rev. C 102, 064602 (2020); H. M. Albers et al., Phys. Lett. B 808, 135626 (2020)] was used in studies in combinations with various actinide targets from ^{238}U to ^{249}Cf. In this work, the impact of the ^{208}Pb closed shells on the mass-distribution yield of quasi-fission products has been investigated. The results reveal that the sequential fission process could be responsible for the origin of the heavy fragments around ^{208}Pb. This indicates that the dynamics of the nuclear reaction towards the synthesis of the heaviest nuclei must be reconsidered.

Nuclear Structure

The experimental study of K isomeric states in the region of the heaviest nuclei is ongoing at TASCA. The analysis of the experimental data on the synthesis of the extremely short-lived ^{252}Rf via its anticipated long-lived K-isomeric state as suggested in [J. Khuyagbaatar, Eur. Phys. J. A 58, 243 (2022)] was finalized. The 2n channel of the ^{50}Ti+^{204}Pb reaction was used to produce this isotope. The presence of a μs-fission activity was observed at beam energies corresponding to the 2n channel. However, for an unambiguous conclusion on the discovery of the new isotope ^{252}Rf, additional data are needed, which are foreseen to be collected in 2024.

The analyses of the experimental data on the fission-fragment mass distributions of ^{252}No, ^{255}Rf and ^{258}Rf measured with the ANSWERS setup in the FAIR Phase-0 beamtimes in 2020-2022 were finalized and will be published. The analyses of the experimental data on the low-lying structure of ^{253}No and ^{255}No were finalized as well and will also be published.

At SHIPTRAP, the buffer-gas cell was extensively tested with the use of radioactive recoil sources to understand and overcome the change in the entrance window thickness due to deposition of contaminants from the beamline during its extended operation online at cryogenic temperatures. A heating system was added closely to the entrance window to ensure the evaporation of the residues from its surface and to maintain a constant stopping efficiency in preparation of the beamtime scheduled in 2024. A systematic optimization study of the mass resolving power of the preparation trap has been performed and different settings for fast/slow ion bunch centering and purification have been established.

The data acquisition software has been updated with a new reconstruction algorithm, which allows recovering incomplete events from the position-sensitive ion detector. The new software is Python-based and is intended to substitute the existing Labview solution, in line with the GSI general migration away from National Instrument software products. A database has been established for a more efficient data storage of all the environmental parameters that must be kept under control during long measurement times.

The analysis of the SHIPTRAP data from the beamtime 2021 has progressed, and specific libraries have been customized. The data analysis of the measurement of ^{257}Rf, as well as of the α-decay chain ^{206}Fr – ^{202}At – ^{198}Bi were finalized. A deeper understanding of some systematic uncertainties requires additional offline measurements. Publications are in preparation.

Atomic Physics

As there was no physics beamtime at GSI in 2023, the program on the laser spectroscopic investigations of the heaviest elements focused on the analysis of the results from the experimental campaigns of the preceding years. The results of 6 on-line produced fermium (Fm, Z=100) isotopes obtained with the RADRIS technique in the FAIR Phase-0 beamtimes in 2020-2022 were evaluated and combined with results on two more fermium isotopes, which were measured off-line at JGU Mainz. The experimental results were complemented by state-of-the-art nuclear model calculations and a comprehensive manuscript reporting on these findings was submitted in 2023. The technical developments and results on probing the opportunities and limitations of in-gas-cell laser spectroscopy of the heaviest elements with RADRIS were published as a proceedings contribution to the EMIS2022 conference [2]. In the beamtime 2022 the new JetRIS setup was commissioned. Here, laser spectroscopy was performed in an effusing gas-jet to improve the spectral resolution, which could be demonstrated on-line with a measurement of the nobelium isotope ^{254}No. Here, a discrepancy to the transition energies with respect to the earlier RADRIS measurements was found, which demanded additional systematic investigations of the used wavemeter to quantify all systematic effects in the photon energy determination. These results were finalized and the manuscript on the in-gas-jet laser spectroscopy of ^{254}No with JetRIS was submitted in 2023. As the efficiency of the setup was found to be not ideal, further investigations with the setup were performed in 2023 to improve the setup and to understand the main sources of losses. An improvement in the efficiency by a factor up to 2 was achieved and the behavior was compared to finite-element computer simulations. This optimization process is still on-going and quite promising that a significantly improved setup is available for the upcoming beamtime, which is scheduled for 2025. Further developments, which took place at the HI Mainz, were performed with a new quadrupole mass spectrometer setup to test and evaluate ionization schemes for later on-line use as well as with the assembly and testing of a new multi-reflection time-of-flight mass spectrometer. The latter will in future extend the capabilities of the group's gas-cell laser spectroscopy program to long-lived nuclides and to nuclides independent of their respective decay mode.

The collaboration with the institute of physics and the department of chemistry at JGU Mainz, which enables measurements of long-lived actinide isotopes with minuscule sample sizes at the RISIKO mass separator, continued also in 2023. The data from previous measurement campaigns yielding nuclear moments and isotope shifts of the actinide isotopes $^{249-253}$Cf probed by laser spectroscopy was published [3]. A new measurement campaign that aims at probing the atomic and nuclear properties of ^{255}Fm was performed in 2023. For this, an ^{254}Es sample from ORNL Oak Ridge, TN, USA was shipped to the high-flux reactor at the ILL Grenoble, France, to breed ^{255}Es ($T_{1/2}$: 40 d) which decays into ^{255}Fm ($T_{1/2}$: 20 h). Using chemical separation techniques, 17 samples of ^{255}Fm became available over the course of about three months. Some of these samples were used for measurements on the atomic fine and hyperfine structure; the data are under analysis. Other samples were used for collaborative work with the GSI Biophysics department, cf. section "Technical developments and key contributions to collaborative work".

Chemical Studies

Building up on the success of experiments conducted during the FAIR Phase-0 beamtime in 2022, our research expanded to explore the properties of Hg, Po, and At isotopes, serving as lighter homologs of the superheavy elements Cn, Lv, and Ts. Collaborating with the CTU Prague from FAIR aspirant partner Czech Republic, we conducted gas-phase chromatography experiments with gamma-decaying isotopes of Hg, At (as homolog of Ts), and Po (as homolog of Lv) at NPI CAS Řež (CZ). We employed a new and versatile setup, designed to study the interaction of Hg, At, and Po with quartz surfaces. The temperatures of the chromatography column ranged from +1000 °C to -55 °C in thermochromatography (TC) studies, and from +350 °C to +20 °C in isothermal chromatography (IC) experiments. The radioisotopes were produced in fusion-evaporation reactions using a 48-MeV ^{3}He-beam, recoiling from the thin target, and thermalized in helium gas. This also served as a carrier gas to transport the volatile At and Hg to the column. Po isotopes were collected in a Ti catcher foil placed directly behind the target during irradiation. After the end of irradiation, the foil was placed in the chromatography column and heated to release the collected Po isotopes. Reactive gases, such as oxygen and hydrogen, could be introduced directly before the chromatography column. In IC experiments with At, the fraction of radioisotopes surviving the transport through the chromatography column was deposited in a charcoal filter measured using a gamma-detector. The experiments revealed a complex interaction of At with the quartz surface. In TC experiments, yielding internal chromatograms, Hg was found not to be adsorbed on quartz, whereas it reacted strongly with Au, which agrees with known data [L. Lens et al., Radiochim. Acta 106 (2018) 949]. The data on At and Po are under final analysis. For these experiments, the MARGE subsystem [4] for production and delivery of radionuclides was extended to house two independent recoil target chambers, which were utilized for two simultaneous and independent experiments using aqueous chemistry and gaseous chemistry in parallel during the same beamtime. Supported by the FAIR-CZ national project, development of an on-line microfluidic aqueous chemistry apparatus for the NuSTAR collaboration continued. As a part of the testing, the early studies of chemical properties of the Sg and Nh homologues were extended; the results are in the final stage of analysis and are planned to be published.

First gas chromatography studies with the short-lived 145-ms isotope ^{216}Po were conducted offline at GSI. The experiments were performed offline using a ^{224}Ra source placed inside the TASCA Recoil Transfer Chamber, to which a miniCOMPACT detection system was attached. The measured chromatograms of ^{216}Po in helium, argon, and oxygen carrier gases point at a rather low volatility of Po species over the silicon oxide surface kept at room temperature.

Chemical Theory Supporting Experimental Work

To assist current gas-phase chemistry experiments on the volatility of At, a homolog of Ts, and to predict the behaviour of Ts in future experiments, calculations of adsorption energies E_{ads} of these elements and their compounds on gold and hydroxylated quartz surfaces were performed using relativistic periodic density functional theory implemented in the AMS BAND software. The following compounds were considered: MO, MH, MO_2, OMO, MOH, MOO, OM(OH) and MO(OH), where M = At and Ts. The obtained values of E_{ads} indicate that all the molecules should interact fairly strongly with the gold surface, with those of Ts being more reactive than the At ones. The similarity of the E_{ads} values of all the considered At compounds will make it challenging to differentiate between them via measurements of their adsorption enthalpies, given experimental uncertainty. However, the differences in E_{ads} among Ts compounds are more pronounced, so that one should be able to differentiate between the species.

Results for the adsorption of At and Ts on the hydroxylated quartz surfaces have shown that elemental At should adsorb very weakly, with E_{ads} of -26 kJ/mol on geminal and -20 kJ/mol on vicinal silanols, while AtH, AtO, AtO_2, and AtOH should adsorb more strongly, with E_{ads} of -30 to -40 kJ/mol. The E_{ads} absolute values of OAtOH, AtO(OH) and OAtO are the largest, reaching 100 kJ/mol. Thus, it should be easy to distinguish between adsorption of elemental At and that of its compounds on the quartz surface, i.e., elemental At should be much more volatile. The corresponding Ts compounds should be more reactive than those of At, i.e., they should adsorb at higher temperatures, than those of At. It should therefore be possible to distinguish between the At and Ts species. Also, the differences in E_{ads} between the various species of Ts are larger than those between the At ones.

Adsorption properties of group 1 and 2 elements and their compounds including those of elements 119 and 120 on hydroxylated quartz surfaces were calculated using a periodic BAND suite [5]. The results show that all the considered group 1 and 2 elements should adsorb rather moderately on the quartz surfaces, with E119 and E120 most weakly, due to the strong relativistic stabilization and contraction of the 8s atomic orbital. This means that E119 and E120 should have a deposition peak in the quartz chromatography column with a temperature gradient from room temperature to far below zero in the sequence Cs/Ba > Fr/Ra > E119/E120. For group-1 element MH and MOH molecules, the adsorption energies are high, so that the adsorption-desorption equilibrium should be reached at very high temperatures, with the following trend in the adsorption strength MH > MOH >> M.

Optimised Norm-Conserving Vanderbilt Pseudopotentials for Actinides and Super Heavy Elements in the PseudoDojo have been developed in a large collaboration with other theory groups. Our work comprised calculations of solid-state structures of the elements using the BAND software. The new approach should allow calculations of solid-state properties of superheavy elements using, e.g., the Quantum Espresso software, at a higher level of theory than presently available.

Technical developments and key contributions to collaborative work

As discussed in the section “Atomic physics”, 17 samples of ^{255}Fm became available over the course of about three months. Five of these samples were used for collaborative work with the GSI Biophysics department to test the uptake and cytotoxicity of ^{255}Fm in prostate cancer cells. For this purpose, five prostate specific membrane antigen (PSMA)-617 samples were labelled with ^{255}Fm; PSMA-617 is a small molecule which binds with high affinity to the transmembrane glutamate carboxypeptidase PSMA that is highly expressed on prostate cancer cells, such as the PC3-PIP cells that were used in this study. Target-specific uptake of ^{255}Fm-PSMA was evaluated by using liquid scintillation counting (LSC) and the effect of the single alpha-emitter ^{255}Fm on PC3-PIP cell proliferation was assessed with the colorimetric MTS assay, confirming a strong dose-dependent decrease in cell viability.

Further work at HI Mainz and JGU involved the development of laser resonance chromatography (LRC) to investigate the atomic structure of superheavy elements [M. Laatiaoui et al., Phys. Rev. Lett.125, 023002 (2020)]. The LRC apparatus is now in operation. The chromatographic performance of the apparatus was evaluated by analyzing the arrival time distributions (ATDs) of laser ablated Hf$^+$ ions and the ATD peak separation when comparing Lu$^+$ and Yb$^+$ ions in their ground states. A metastable ATD peak was observed for the first time in the Lu$^+$ arrival time distributions. The LRC was also successfully demonstrated for the first time by initiating the optical $^1S_0$-$^3P_1$ ground state transition in this ion at about 28,503 cm^{-1}, allowing optical pumping to the metastable $^3D_1$ state. We measured the hyperfine parameters of the $^3P_1$ state in ^{176}Lu$^+$ and determined the isotopic shift of the spectral line relative to that of the more abundant ^{175}Lu$^+$. To measure the extraction and transmission efficiencies, ^{219}Rn$^+$ recoil ions from a ^{223}Ra source were used. In a typical bunching operation, the overall efficiency of the device was found to be 0.6 %. Before conducting future studies at in-flight separator facilities, the LRC technique needs to be further optimized to investigate the spectral precision of the method and improve the overall efficiency of the apparatus. Further efforts have been made to investigate the transport properties of heavy metal ions in buffer gas environments. The studies complement the LRC investigations and provide a deeper understanding of the underlying ion-atom interactions. For this purpose, a Cryogenic Ion Mobility Spectrometer (CIMS) was designed, developed, and recently put into operation. Systematic investigations of ion mobility in a wide range of reduced electric fields were carried out for some lanthanides and transition metals, and metastable states were observed for some of them for the first time. This research will be extended to actinide cations in the future.

At HI Mainz and in collaboration with the GSI Materials Research department, work is ongoing towards the production of improved f-element targets for accelerator experiments, optimized for coping with highest beam intensities as they will become available, e.g., with HELIAC. Novel developments in electrochemistry were transferred to target production, employing anhydrous electrochemical routes. The produced thin layers were characterized by a variety of analytical methods, irradiated with ^{48}Ca ions at TASCA/X8 and with ^{197}Au ions at M3, and characterized again after irradiation. The study is published in [6].

Also at HI Mainz, the production of tailor-made samples of exotic radionuclides continued to be an important pillar of the SHE Chemistry program. Besides the ^{255}Fm samples described above, optimized samples of ^{242}Pu for the production of the fission isomers in ^{240,242}Am at the IGISOL facility at U. Jyväskylä (SF) were delivered and successfully used in an accelerator experiment at Jyväskylä. Samples of ^{232}Th were prepared for collaborative work with U. Gothenburg and U. Stockholm for experiments at the Stockholm DESIREE storage ring. Studies on the formation of few-atom clusters of thorium and uranium were carried out in collaboration with U. Greifswald.

The chemical study of elements beyond Mc requires the development of novel techniques to efficiently transfer short-lived isotopes with half-lives below 100 ms to a gas chromatography detector array. The proposed universal buffer gas stopping cell (UniCell) [V. Varentsov et al., Nucl. Instrum. Meth. A 940 (2019) 206] is based on the radiofrequency (RF) ion-funnel technique and is designed to succeed the TASCA recoil transfer chamber. Ion trajectory simulations for UniCell were carried out using SIMION. A setup with DC field strength E = 100 V/cm, temperature T = 300 K, helium pressure P = 1 bar, and peak-to-peak RF amplitude V_{pp} = 200 V was found to be desirable as the optimum choice for an extraction efficiency of 100%. The extraction time was calculated to be about 4.4 ms and 2.2 ms for ions of mass 293 amu and charge states 1+ and 2+, respectively. The fabrication of the UniCell RF-funnel assembly consisting of 350 electrodes was performed by our collaborators at ITE Cracow, Poland. Mechanical design on its integration and the development of suitable electronics have commenced. First tests with radioactive sources to start the commissioning of the device are being prepared. In the next step, the offline test of UniCell will be carried out to benchmark the simulation results. In addition, the high-pressure Ion Transfer by Gas Flow (ITGF) device to couple UniCell to the COMPACT detection setup was proposed and initially studied using COMSOL Multiphysics®. The ITGF transport time decreases with increasing gas flow rate. After optimizations of the ITGF, the flow rate is selected to be more than 20 mL/s, and the time to pass through the ITGF device is only about 0.2 ms. The results of the above simulations are in preparation for publication.

The focal-plane area of the TASCA separator (cave X8) was reconstructed in preparation for the ANSWERS spectroscopy beam time in 2025. The whole area where the ANSWERS setup is installed was surrounded by shielding that resembles a hut with a movable door. The effect of this extra shielding on the neutron-background was tested during the engineering run in November 2023 together with the Radiation Safety Department. The result demonstrated a substantial decrease (about a factor of ten) in the neutron-background.

In the process of replacing the 40-year-old SHIP magnet power supplies, new power supplies for the quadrupole magnets were delivered and installed. This process was performed together with the GAT, EPS and ACO groups of GSI. The functionality of the new power supplies was tested in the engineering run in November 2023. Here, one day of ^{40}Ar beam was used with ^{169}Tm and ^{208}Pb targets, The obtained results of the fusion products in rate and spatial distribution match the expectations and thus SHIP is again ready for the upcoming physics beamtime 2024. The dipole magnet power supplies are next to be exchanged.

Outlook for 2024

At SHIP, a main beamtime with ^{40}Ar and ^{50}Ti beam to perform mass measurements of the ground and isomeric state of ^{258}Db and lighter Fr, At, and Bi isotopes is scheduled for SHIPTRAP in 2024. The experiment aims at disentangling the ground state from the low-lying long-lived metastable state and at accurately determining its excitation energy. Taking into account the half-lives of these two states, the tentative identification of the ground and isomeric state in ^{258}Db provided by previous decay spectroscopy studies at SHIP [M. Vostinar et al., Eur. Phys. J. A 55, 17 (2019)] can be verified. However, this measurement is quite challenging as the count rate of ^{258}Db is of the order of 1 ion every 5 hours at the SHIPTRAP position-sensitive detector. A second, parasitic beam time with chromium beam is planned at SHIP and is scheduled for May 2024; it will be devoted to laser spectroscopic studies with lutetium isotopes, the iso-electronic homologue of $_{103}$Lr. Here the desorption behaviour with the RADRIS technique will be evaluated to understand the expected behaviour of Lr, for which an extended level search is foreseen in 2025.

At TASCA, chemistry studies towards seaborgium carbonyl complex formation and its reactivity, volatility, and the chemical stability are planned for 2024. The newly tested combined detection system, miniCOMPACT plus COMPACT, allows for studies of carbonyl complexes with very short-lived isotopes of the superheavy elements, which can be produced in cold fusion reactions for elements up to $_{107}$Bh, with larger production rates than more long-lived isotopes from hot fusion reactions. This will open the perspective for the first study with carbonyl complexes of Bh, which are unknown yet.

The chemistry studies at NPI CAS Řež will continue with another beamtime in spring 2024 to further the understanding of the properties of Hg, Po, and At in contact with quartz surfaces, and the offline studies with ^{216}Po will be extended to cover a wider temperature range. These will be accompanied by theoretical work on the volatility of Po, a homolog of Lv, yielding predictions of the adsorption behavior of these elements and their compounds on surfaces of gold and quartz on the basis of the relativistic periodic DFT calculations. Thermodynamic properties of SHEs as a function of temperature are planned to be investigated as well.

Selected publications of 2023

- [1] Jeung, D.Y.; Hinde, D.J.; Dasgupta, M.; et al.: Sequential fission and the influence of ^{208}Pb closed shells on the dynamics of superheavy element synthesis reactions. Phys. Lett. B 837, 137641 (2023), DOI:10.1016/j.physletb.2022.137641
- [2] Raeder, S.; Anđelić B.; Auler J.; et al.: Opportunities and limitations of in-gas-cell laser spectroscopy of the heaviest elements with RADRIS., Nucl. Instrum. Methods Phys. Res. Sect. B, 541, 370-374 (2023), DOI:10.1016/j.nimb.2023.04.044
- [3] Weber, F.; Albrecht-Schönzart T.; Allehabi, S.O., et al.: Nuclear moments and isotope shifts of the actinide isotopes $^{249-253}$Cf probed by laser spectroscopy. Phys. Rev. C 107, 034313 (2023), DOI:10.1103/PhysRevC.107.034313
- [4] Bartl, P.; Běhal, R.; Matlocha, T.; et al.: MARGE — a new ModulAr Robotic Gas-jet targEt system for chemistry studies with homologues of superheavy elements. Nucl. Instrum. Methods Phys. Res. Sect. A, 1052, 168280 (2023), DOI:10.1016/j.nima.2023.168280
- [5] Pershina, V; Iliaš, M: Theoretical predictions of properties and adsorption behavior of group 1 and 2 elements, including elements 119 and 120, on the surface of gold from periodic DFT calculations. Mol. Phys. e2237614 (2023), DOI:10.1080/00268976.2023.2237614
- [6] Meyer, C.-C., Artes, E., Bender, M., et al.: Fabrication, swift heavy ion irradiation, and damage analysis of lanthanide targets. Radiochim. Acta 111, 801-815 (2023), DOI:10.1515/ract-2023-0197

5. Research of the PANDA Departments

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

The PANDA experiment (s. Figure 52) belongs to a new generation of hadron physics experiments, hereby building on the experiences and successes of previous generations. It features a modern multipurpose detector. The combination of a high-quality antiproton beam at the High Energy Storage Ring (HESR), an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. GSI is the PANDA lead-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 and the experiment infrastructure and the Gas Electron Multiplier (GEM) detector. This is accompanied by Phase-0 activities involving PANDA hardware like PANDA@HADES, PANDA@MAMI, PANDA@ELSA in Darmstadt, Mainz and Bonn respectively and cooperation for the GlueX-DIRC at Jefferson Lab (Newport News, USA) as well as data analysis at GlueX and BESIII at IHEP (Beijing, VR China). To accomplish the goals, the department teams up inside GSI with the Electronics Lab, Detector Lab and the sections EMP and SPECF of the Helmholtz Institute Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

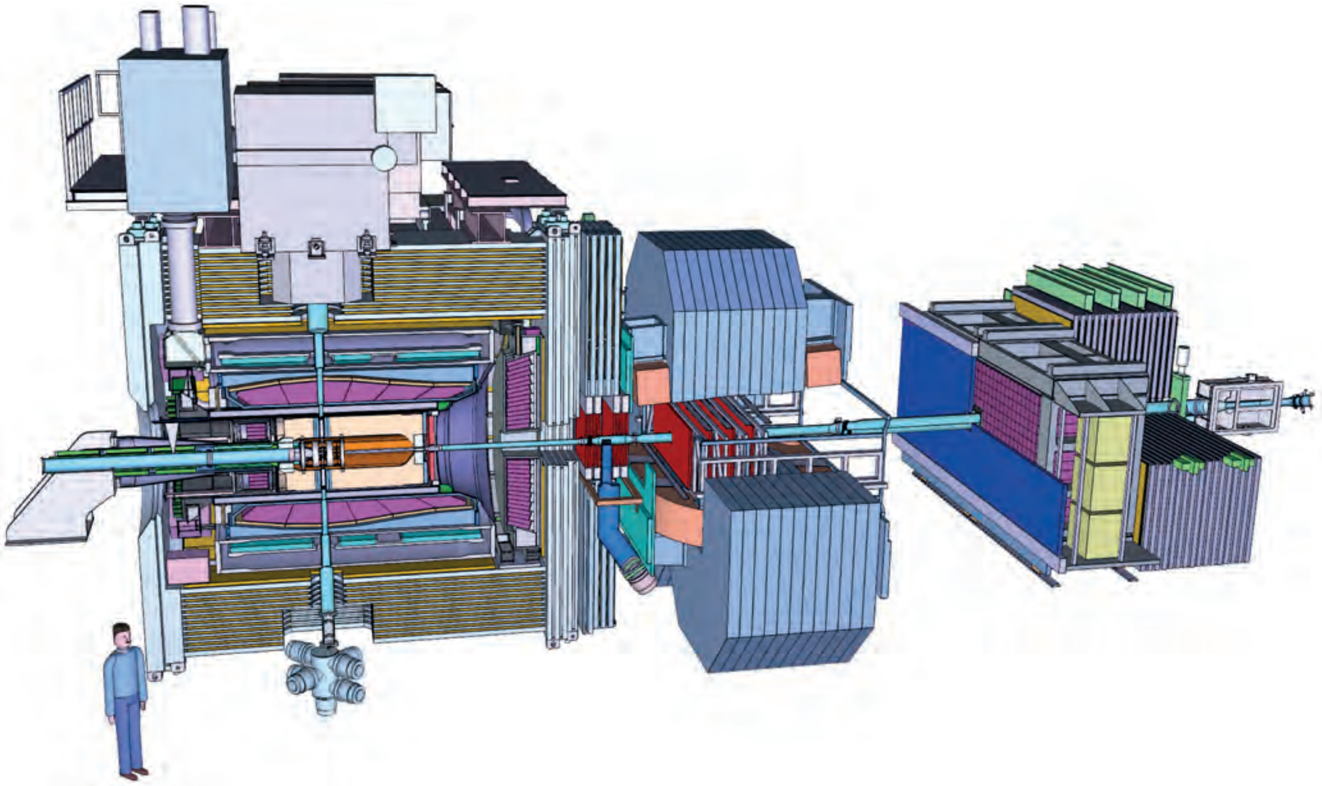

Figure 52. PANDA Detector (Illustration by J. Lühning, GSI).

5.1 Hadron spectroscopy

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

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 Electromagnetic Calorimeter (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 optimization of the detector as well as its operation and analysis.

Highlights in 2023

Work of the PANDA Coordination Group

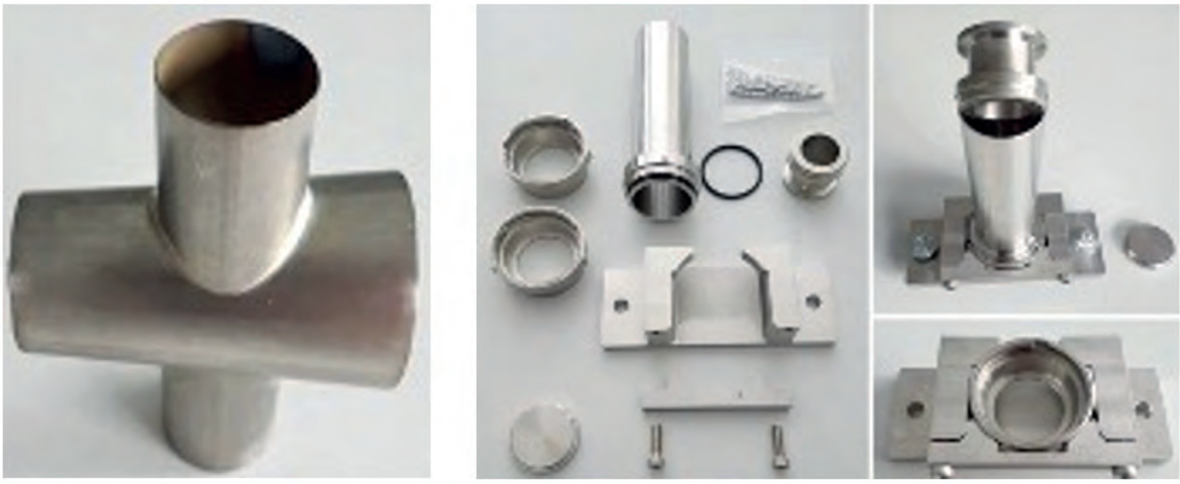

Figure 53. Left: Titanium cross prototype; right: bayonet prototype.

In March 2023 a workshop was held at FZ Jülich to hand over the design of the PANDA beam-target pipe done until that point at ZEA1 of FZ Jülich. The design work, safety considerations, welding procedures and special devices like bayonet flanges and procedures for insertion and extraction were discussed. Prototypes of flanges and pipes were handed over to the GSI team (see Figure 53).

In parallel to this activity the development of ultra-high vacuum pipes based on CFC was started, both as a general technology development and as alternative to the Titanium based beam-target pipe of PANDA. The development is supported by the GSI innovation fund, as a technological spin-off of a successful development may have multiple applications in vacuum industry and elsewhere.

Following the EU sanctions in response to the Russian attack on Ukraine the contract with BINP Novosibirsk for the superconducting solenoid of PANDA was cancelled in fall 2022. A potential procurement of the magnet from European companies would require having a superconducting cable available. As the magnet due to its size and field has a high energy content, an Aluminum stabilized conductor is the expert choice regarding safety and stability. However, currently there is no such conductor on the market. Developments for future magnets are anticipated at CERN and take place in China for CEPC, but both are for projects with longer time horizons. With the specification by the FAIR management of a completion of the modularized start version (MSV) by 2032 the risk of not having a magnet in time for PANDA was assessed.

An alternative option would be the use of the existing superconducting coil of ZEUS/HERA available at DESY. This however has some repercussions on the setup of PANDA which were extensively studied by the PANDA coordination group in the course of 2023. The first critical item in this regard is the need for a horizontal target pipe traversing the magnet at 30° as the ZEUS coil does not have an opening for a pipe perpendicular to the beam axis. In addition, the diameter of the magnet's warm bore is smaller by 180 mm. This leads to the necessity to arrange the PANDA Barrel EMC slices at a smaller radius. Keeping the original slice design some losses are expected for higher energies at the rear of the slices. Almost full coverage can be reached with 12 instead of 16 slices. Later, the ZEUS coil could be replaced with a new coil with vertical bore to use the high-rate PANDA target requiring vertical operation. Then the remaining gap in the Barrel EMC can be closed with two smaller special slices. See Figure 54 for an artistic view.

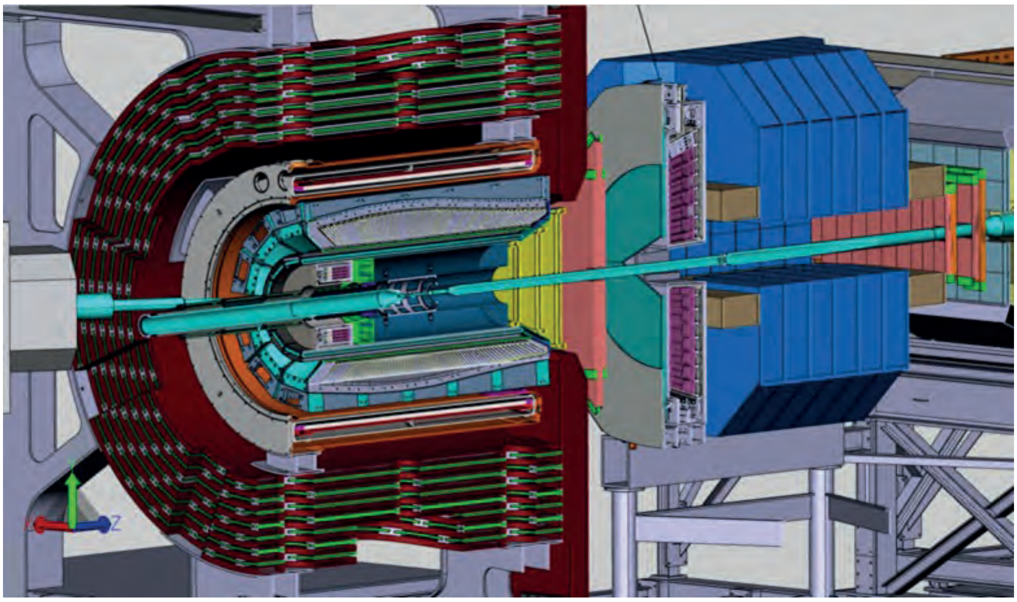

Figure 54. Setup study for PANDA based on ZEUS magnet.

Because of the smaller radius of the ZEUS coil the acceptance of the Forward Endcap EMC is not fully covered anymore at its nominal position within the solenoid yoke. A better position would be approx. 80 cm further downstream outside the solenoid yoke. This results in a smaller acceptance for the forward spectrometer, which however still matches the tracking coverage of the detectors already under construction. One can then employ a smaller, more cost-effective dipole magnet in the forward spectrometer and use smaller detectors for particle identification and calorimetry behind the dipole. PID detectors and dipole are as well missing as contributions from Russia. The discussed modifications need verification with simulations to evaluate their impact on the physics performance of the modified setup. First studies regarding the geometry of the Barrel EMC were started at U Bonn at the end of 2023 with input from the PANDA coordination group.

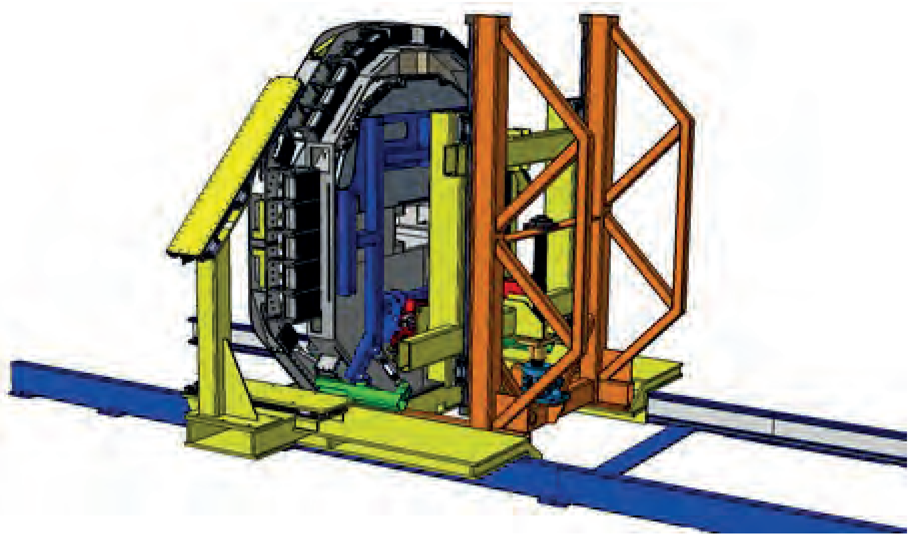

Figure 55. CAD of mounting device and support for Forward Endcap at ELSA.

To assist with the implementation of the PANDA Forward Endcap EMC for an intermediate application at the CB-ELSA experiment at U Bonn the coordination group started the development of a mechanical structure for the insertion, alignment, and support of the detector at the location at ELSA in Bonn (see Figure 55). The design incorporates elements required for a mounting device for the Forward Endcap at PANDA.

Outer Tracker

Figure 56. (Left) The OT in the air at port Gernsheim, (Right) The OT moved into storage at GSI.

The Outer Tracker straw tube detector of LHCb has arrived at GSI in August 2023. The transport took five days, starting at CERN on a truck, the journey continued by boat on the river Rhine up to port Gernsheim where a truck brought the OT safely to GSI. Due to the oversize width (3.5 m) and height (5.5 m), and weight 24 t, special traffic regulations were enforced en route. The detector in its transport frame is now stored in a hall on the GSI campus (see Figure 56).

During transport and storage two sensor units attached inside the transport frame took measurements of temperature and rel. humidity, at regular intervals, keeping the data on a local storage card. An effort started to develop an automated remote monitoring system for multiple sensor units distributed within the detector volume.

The readout board developed at GSI/EEL to interface the original ASICs with the PANDA DAQ system is being tested with several ASICs available with a module system test planned in 2024. The software description of detector modules has been successfully implemented in the simulation software PANDAROOT by a GSI summer school student in summer 2023, allowing to start simulation studies.

The arrival of the detector has sparked interest to use parts of the modules at various beamlines at GSI/FAIR and elsewhere, in addition to PANDA.

PANDA Barrel EMC – Slice-0

The design of the PANDA Barrel EMC is subdivided into slices facing the interaction region. Slice-0 is the first slice to be completely assembled and tested under real operations conditions at -25°C. The readout for slice-0 is based on the ASIC developed at GSI/EEL.

All mechanic components for all slices have been produced and stored at JLU Giessen, but the absence of the Russian institutes, formerly involved in the production and construction, necessitates the stronger involvement of the technical coordination group (TC) with priority to complete slice-0.

The TC team visited JLU Giessen and together with the EMC system group conducted a "Barrel EMC Inventory Review". The review encompassed updates on the CAD model, updates on the status of each work package and inspection of all mechanical components and assembly tools. Emphasis was given to the tasks to complete slice-0. At GSI/EEL we plan to mount all ASICs on the PCBs for slice 0 and conduct functional tests before they are released for installation into slice-0 a JLU Giessen the end of 2024.

PANDA Software Trigger

The results of the study for the PANDA Software Trigger supported by machine learning techniques aiming at signal efficiency optimization for a fixed accepted background rate were published in the peer-reviewed journal

EPJC. The final network choice was 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. Adding event shape input variables lead to further improvement of data quality could.

HepFastSim - A lite-weight Fast Simulation Framework

In order to address design studies of future detector setups in a flexible way, a stand-alone Fast Simulation Framework named “HepFastSim” has been developed. It does not depend on any other software except a ROOT installation and and thus is very portable, easy to install and use without much expertise. It features parametrized detector configurations of tracking- and photon-detectors as well as detectors for particle identification. It allows various ways of event generator input and brings a box generator and a phase-space decayer for arbitrary decay channels. For analysis of the generated and simulated events, the software is capable to perform reconstruction including combinatorics, selection, Monte Carlo truth matching, 4-constraint fitting and vertexing. It stores the reconstructed candidates in ROOT TTrees and is able to generate live histograms during the simulations process for immediate feedback. The typical processing speed is between 1 kHz and 10 kHz, depending on the complexity of the simulation task. Thus, it is a very effective and efficiency tool to quickly perform studies about expected kinematic distributions, signal-to-noise ratios, acceptances and even efficiencies for almost arbitrary physics reactions and detector configurations. After more and thorough testing, it is intended to be published in 2024.

FAIR Phase-0: Analysis of GlueX Data

The analysis of the search for $\varphi(2170)$ in reactions γp -> $\varphi\pi^+\pi^-p$ in three photon scattering data sets recorded between 2017 and 2018 with the GlueX detector has been completely refocused to a measurement of the differential production cross section $d\sigma(\gamma p$ -> $\varphi\pi^+\pi^-p)/dm$ across the masses $m(\varphi\pi^+\pi^-)$ and $m(\pi^+\pi^-)$. As a result, two resonant structures are observed in the $m(\varphi\pi^+\pi^-)$ at around $m = 1820$ MeV/c^2 and $m = 2240$ MeV/c^2. The first resonance has a significance of about 3σ including systematic uncertainties, the second a significance of about 5σ. It confirms a structure previously observed by BESIII in the context of searches for the exotic candidate $\varphi(2170)$ in the decay channel K^+K^-. The three observed structures in $m(\pi^+\pi^-)$ can be well identified with known resonances with high significance. The preliminary results have been presented on the HADRON2023 as well as the MESON2023 conferences. The analysis is currently in the internal GlueX review process and is intended to be published as PRL in the course of 2024.

Outlook for 2023

The main objectives for the coming year are:

- Further investigation of alternative PANDA setups.
- Redesign of some PANDA components and respective integration aspects.
- Outer Tracker system tests.
- New BESIII analysis on X, Y, Z states in e^+e^- annihilation using ML techniques.

Selected publications of 2023

- P. Jiang, K. Götzen, R. Kliemt et al (all GSI), “Deep Machine Learning for the PANDA Software Trigger”, Eur. Phys. J. C 83, 337 (2023). DOI:10.1140/epjc/s10052-023-11494-y
- A. Belias (GSI) for the PANDA collaboration, “Overview of the PANDA detector design at FAIR“, DOI:10.1142/S2010194523600017, Published in: Int.J.Mod.Phys.Conf.Ser. 51 (2023), 2360001
- M. Aehle (Unlisted and Kaiserslautern U.), Lorenzo Arsini (U. Rome La Sapienza (main) and INFN, Rome), R. Belén Barreiro (Cantabria Inst. of Phys.), A. Belias (GSI), Florian Bury (Glasgow U.) et al., “Progress in End-to-End Optimization of Detectors for Fundamental Physics with Differentiable Programming“, e-Print: 2310.05673 [physics.ins-det]

5.2 Department PANDA Detectors

Head: Dr. Jochen Schwiening (GSI)
Authors: Roman Dzhygadlo, Andreas Gerhardt, Jochen Schwiening

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

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. The series production of the micro-channel plate PMT (MCP-PMT) sensors, which started in 2022, continued in 2023. The quality assurance of the sensors is performed at Erlangen University. The optimization of the procedure for the gluing of the PANDA Barrel DIRC bars at HIM continued and the final design review is expected to take place in early 2024. A significant milestone in the mechanical design for the PANDA Barrel DIRC was reached with the fabrication of the first full-size readout box prototype. The design of the high-performance barrel DIRC for the ePIC experiment, a joint effort of GSI and several U.S. universities and labs, successfully passed the EIC project review in 2023.

Application of Machine Learning for the Barrel DIRC

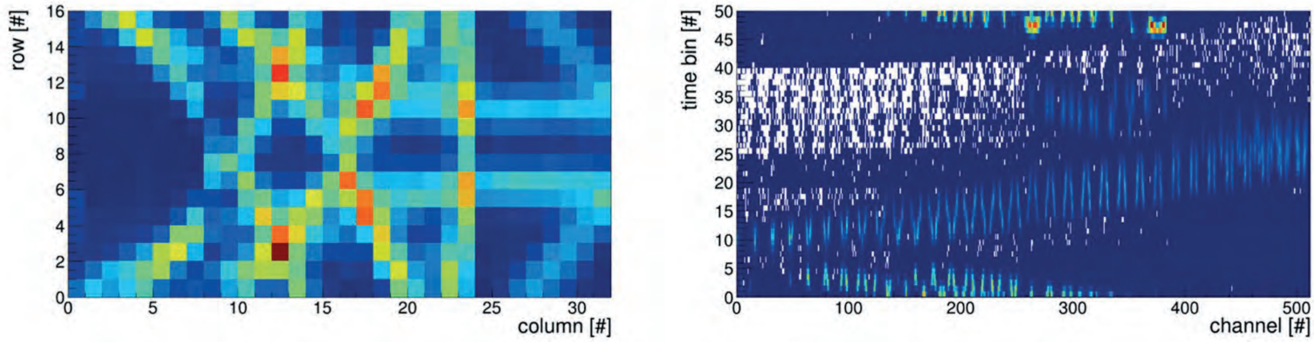

Figure 57. Input data structure based on position (left) and both position and time data (right). Accumulated for 20k charged pions at 20° polar angle and 7 GeV/c momentum.

A new reconstruction algorithm, based on machine learning techniques, is currently in the development for the particle identification with the PANDA Barrel DIRC. In contrast to conventional reconstruction methods, which were developed in the past for the DIRC detectors in the BaBar and Belle-II experiments and optimized for PANDA, the machine learning approach may present additional benefits as it optimizes the use of the time and position information of the DIRC detector at various track parameters. This could lead to a more robust reconstruction, faster information processing, and potentially to a better performance. As the first step we investigated a simple neural network (NN) for fixed track parameters. The input data are represented by an indexed list of hit location and binned detection times. Figure 57 shows an example of the input accumulated for 20k pions simulated using the Geant4 simulation of the PANDA Barrel DIRC prototype setup from a test beam at CERN in 2018.

In the first layer of the NN, the indexed data are expanded into a tensor where each element represents binary data. A combination of convolutional and max-pooling layers is used to extract features of the data, which are further processed through a flattening layer into a fully connected layer to perform the classification task (see Figure 58, left). The current architecture of this NN-method already reaches a performance close to the best classical reconstruction method, time-imaging reconstruction, as shown in Figure 58 (right). The future R&D will be focused on including additional track parameters, such as direction, momentum, and the intersection point of the particle on the bar, into the NN.

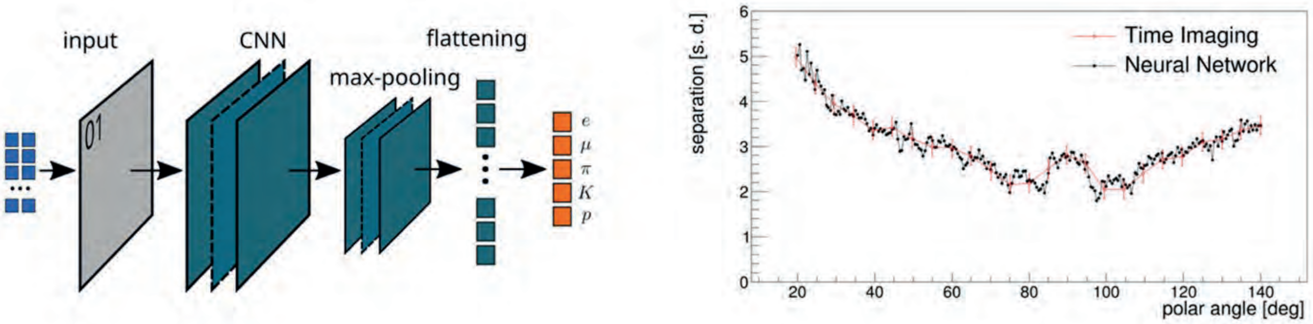

Figure 58. Neural network architecture (left) and comparison of the performance of neural network and the traditional time imaging reconstruction, shown as π/p separation power as a function of the particle polar angle for a momentum of 7 GeV/c (right).

Design and First Prototype of the Readout Module for the PANDA Barrel DIRC

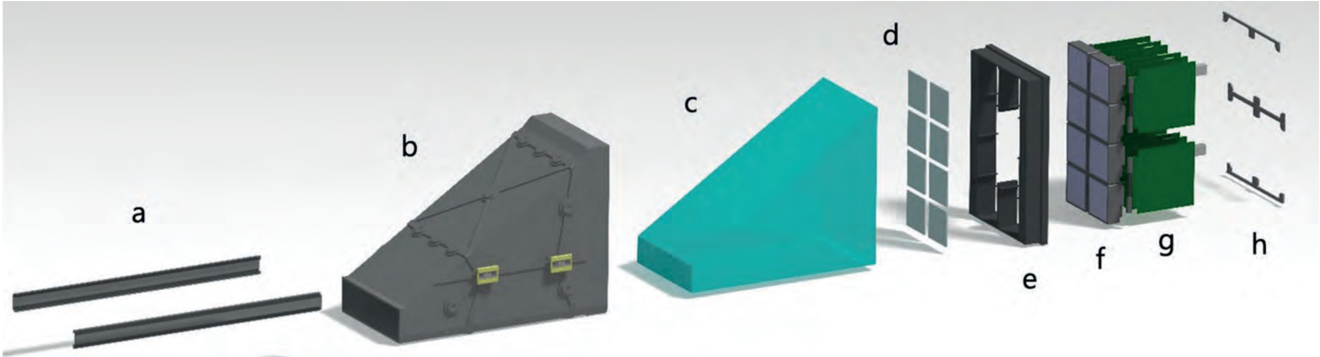

Figure 59. Exploded CAD view of the main components of the readout module for the PANDA Barrel DIRC (see text).

The design of the PANDA Barrel DIRC detector is based on 16 optically isolated modules, arranged in a barrel around the interaction point. Each module consists of one bar box, which contains three fused silica bars where the Cherenkov light is created and transported by total internal reflection to the lenses at the end of the bar, and one readout box, where the photons expand in a large, fused silica prism before the arrival location and time is measured on an array of MCP-PMTs. This information, together with the momentum of the particle, measured by the PANDA tracking system, will be used to identify the particle type with high efficiency and accuracy.

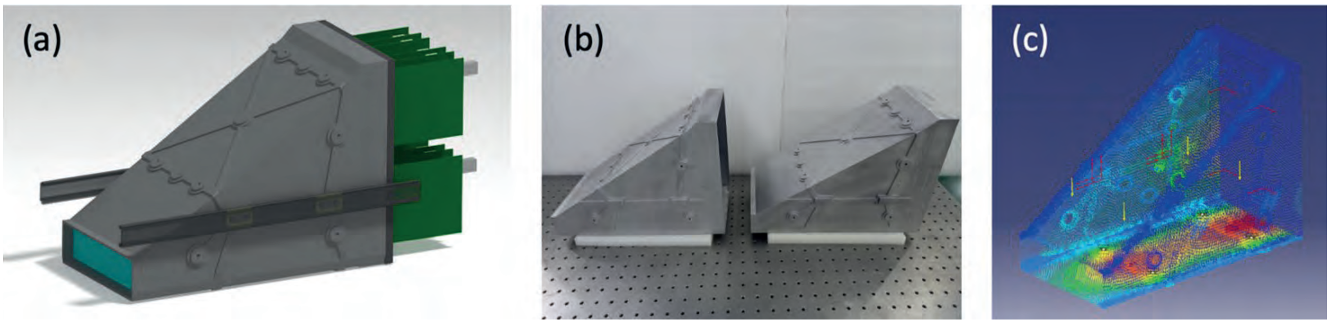

Figure 60. CAD view of the mechanical assembly of the PANDA Barrel DIRC readout module (a), photo of the first two prototype readout box covers at GSI (b), and finite elements (FEM) calculation of the deformation caused by loading the prism cover with the fused silica prism (c).

Each of the fused silica prisms is placed in a light-tight box, which is coupled with a silicone cookie to the lens-end of the bar box. The mechanical design of the prism box was completed in 2023 and is shown in Figure 59 and Figure 60 a. The main components are: (a) rail guides that precisely position the readout box with respect to the bar box, (b) the light-tight cover, (c) the fused silica prism, (d) optical cookies coupling the prism to the sensors, (e) a mounting grid to locate and support the sensors, (f) the array of 8 MCP-PMTs, (g) the DiRICH front-end readout boards, and (h) fixing brackets. The first two prototypes of the prism cover were fabricated by industry and delivered to GSI in December 2023 (Figure 60 b). The covers were designed to be 3D-printed, using a light-weight, high-strength aluminum alloy (AlSi10Mg). FEM calculations, shown in Figure 60 c, were carried out for each of the various orientations of the prisms inside the readout modules for PANDA to ensure sufficient stability of the cover, including a large safety margin. The contact points between the prism and the cover (made of polyether ether ketone, PEEK) are secured by appropriate reinforcement of the cover structure. The prototype covers make it possible to perform measurements, scheduled to be completed in 2024, to validate the FEM calculations and test the mounting procedure, DiRICH cooling, as well as the coupling and decoupling procedure between the lens and prism, as well as between the prism and the MCP-PMTs, using silicone cookies.

Outlook for 2024

The series production of PANDA Barrel DIRC MCP-PMTs and the quality assurance measurements of the sensors will continue in 2024. The ongoing long-term tests of the impact of outgassing from new bar box materials on the optical properties of the DIRC bars is expected to conclude in 2024 and lead to the decision about the final design of the bar boxes. The first prototypes for the bar box and readout box, obtained in 2022 and 2023, will be tested for stresses and mechanical integrity and used in mock-up tests of the installation procedure. The technical design report for the ePIC experiment is due in late 2024, with approval of CD-3 by the US DOE expected in early 2025.

Selected publications of 2023

- R. Dzhygadlo et al., The PANDA Barrel DIRC, Nucl. Instr. and Meth. Phys. Res. Sect. A 1055 (2023) 168480, arXiv:2401.06708
- D. Miehling et al., Lifetime and Performance of the very latest Microchannel-Plate Photomultipliers, Nucl. Instr. and Meth. Phys. Res. Sect. A 1049 (2023) 168047, arXiv:2311.16676
- S. Krauss et al., Performance of the most recent Microchannel-Plate PMTs for the PANDA DIRC detectors at FAIR, Nucl. Instr. and Meth. Phys. Res. Sect. A 1057 (2023) 168659, arXiv:2311.16698

6. FFN (FAIR Forschung NRW)

Head: Prof. James Ritman (GSI, Ruhr-Universität-Bochum & FZ-Jülich)

6.1 HADES

Head: Dr. J. G. Messchendorp (GSI)
Authors: W. Esmail (GSI), A. Foda (GSI), J. Gollub (RU-Bochum), V. Kladov (GSI, RU-Bochum), R. Kliemt (RU-Bochum), J.G. Messchendorp (GSI), S. Pattnaik (GSI, RU-Bochum), G. Perez-Andrade (GSI, RU-Bochum), J. Ritman (GSI, RU-Bochum, FZ-Jülich), S.K. Sahu (GSI, RU-Bochum), J. Taylor (GSI), P. Wintz (FZ-Jülich)

Highlights in 2023

Evaluation of proton-proton reactions to investigate hyperon production

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. In the past years, 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.

Most of the activities in 2023 were dedicated to the analysis of proton-proton scattering data taken in 2022 with a proton beam of T=4.5 GeV kinetic energy impinging on a 5 cm thick liquid hydrogen target. This includes the alignment, particle identification, and track reconstruction of the detector (particularly related to the Forward Detector (FD)), luminosity determination, the (exclusive) event selection of channels of interest, the development and usage of high-level analysis tools, and the first preliminary physics analysis of various channels of interest.

To support the analysis of exclusive channels, 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 successfully implemented and rigorously tested as an external library for HYDRA, the HADES software package. Meanwhile this library is used extensively within the HADES collaboration and the work has been published [1].

Another important technological development supporting the reconstruction analysis of HADES involves novel machine-learning algorithms for particle identification. The conventional approach used in HADES is to apply so-called “graphical cuts” around the theoretical Bethe-Bloch curves. A promising and more powerful alternative approach is to utilize deep learning algorithms. For this, we developed a neural network algorithm that 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.

Various physics channels are presently being studied using the proton data collected by HADES. Some of these studies make use of the developed kinematic fitter and PID methods described above and were, thereby, used to demonstrate the excellent potential of these methods allowing high purity event selection. More specifically, the following reactions are presently being studied by the HADES-FFN group:

- p+p -> Λ+K_S+p+π^+. This channel allows for a study of, and search for, new baryon resonance coupling to hyperon final states complementary to earlier partial-wave analysis studies of the p+p ->Σ^0/Λ+K^++p reaction. The preliminary analysis revealed a clean signature of the final state of interest with various intermediate baryon and meson resonances playing a role.
- p+p -> $\Xi^{\wedge}$-+ K^++K^++p. The objective is a first cross section measurement or upper limit determination for the elementary production of cascade hyperons. The aim is to use such measurement to shed light on the striking enhancement of the near-threshold cascade production observed in heavy-ion reactions. Next to the cascade channel, the control channel p+p ->Σ^- (1385)+K^++π^++p is being analyzed whereby the Ξ^- and Σ^- (1385) share the same final state, namely π^- Λ. A clear signature of the Σ^- (1385) has been identified in the analysis and cut-sensitivity studies for the Ξ^- decay identification have been carried out with the aim to optimize the statistical significance.

- p+p -> p+p+K^++K^- (+π^0). This channel is exploited to study the hidden-strangeness production (i.e., Φ -> K^+ K^-) and to search for intermediate resonances that couple to Kπ and pK. A clear signature of the p+p -> Φ+p+p reaction has been observed with the help of the kinematic fitter and the PID method based on machine learning outlined above.
- p+p -> p+p+e^++e^-+π^0. The ultimate goal is to probe the electromagnetic properties of the Δ^+ via form factor studies of radiative transitions, e.g., Δ -> γ^* Δ. The objective of this work is a feasibility study demonstrating the capabilities of low-mass virtual photon detection in elementary reactions. A dedicated event generator that incorporates the radiative transition process has been developed in 2023 by extending the PLUTO library.
- p+p -> p+p. This channel is used to determine the time-integrated luminosity of the Feb22 run. Moreover, it provides information on the underlying dynamics that take place in this elementary process as a reference to heavy-ion reactions. Differential cross sections have been extracted from the data and are close to being published. The figure below shows some of the preliminary results of this measurement in comparison with data obtained at Argonne at similar energies [2].

Figure 61. Differential cross-section of p-p elastic scattering from HADES at p_{beam} = 5.392 GeV/c as a function of the 4-momentum transfer |t| and compared with data from [2]. The measured cross-section is well described by a function of the form $d\sigma/dt=Ae^{-B|t|}$, from which the optical point parameter A and the nuclear slope parameter B are obtained.

Besides the HADES-data analysis activities, the group has been involved in future developments that potentially connect to the challenges of the next generation experiments such as CBM and PANDA. Particularly, the development of artificial intelligence (AI) techniques for experiment control started in the framework of NRW-FAIR network with HADES data as a proof-of-principle. As the first step, calibration constants (gains) of HADES' drift chambers were predicted for Feb22 experiment. Predictions are based on the neural-network with Long-Short-Term-Memory cells (LSTM) and graph structure to enhance regularization and to account for correlations between multiple channels. Developed method demonstrated the ability to provide fast and stable calibration predictions with a precision comparable to that obtained using traditional offline, time-consuming approaches. With slight changes in the network, predictions can be used to dynamically tune high voltage on the chamber's wires to achieve stable gain during experiments.

Partial Wave Analysis tools and application to pion induced reactions

Preparation studies are ongoing for the upcoming pion-beam at HADES. The pion beam offers a unique opportunity to study baryonic resonances generated at a fixed center of mass energy (√s). Moreover, they are complementary to photo-induced studies and possess a significant advantage over proton-induced reactions. We employ a Partial Wave Analysis (PWA) to investigate how these resonances couple to various final states, with a keen interest in the role of the in-medium effects of vector mesons in baryon-rich heavy-ion collisions. In-depth elementary pion-induced studies on protons, coupled with a PWA, are expected to shed light on the intricate couplings of baryonic resonances to ρN and ωN final states. These studies are particularly crucial for understanding the ρ meson's behavior in heavy ion collisions and the role of intermediate vector mesons in dilepton production. With a view towards a more exhaustive exploration in pion-proton collisions, the team is developing a K-Matrix & N/D frameworks implementation in a modular software package. This advancement aims to precisely map the resonance regions, facilitating the extraction of resonance parameters such as mass, width, and contributions to various channels. We have conducted a sensitivity case study of the double resonance behavior of the N(1720) hinted by the CLAS collaboration using Monte Carlo simulated events. This study demonstrated the feasibility of the upcoming pion-beam experiment with HADES to confirm and disentangle the double resonance behavior.

HADES STS as input to DRD1

The DRD1 Collaboration at CERN has been formed in 2023. According to the 2021 ECFA detector research and development roadmap, the DRD1 collaboration will be devoted to detector research and developments in the broad range of gaseous detector technologies, such as Micro-Pattern Gas Detectors (MPGD), Resistive Plate Chambers (RPC), Time Projection Chambers (TPC), large drift chambers, straw tube chambers, and other wire-based detectors like Thin-Gap Chambers and Cathode Strip Chambers [4]. The addressed field of applications ranges from future accelerator and non-accelerator-based particle physics experiments, nuclear and neutrino physics, Dark matter, and rare decays to medical, industrial, and civil security applications.

A comprehensive collaboration proposal document was worked out in a series of symposium and workshop meetings and submitted to CERN by the end of 2023. The document gives a detailed overview of the current state-of-the-art, the challenges, and future perspectives related to the various gaseous detector concepts and technologies. It also describes the proposed scientific organisation with, at current, nine explicit R&D work packages for different gaseous detector technologies and common R&D topics which are addressed by various work groups. After a review process in late 2023 by the CERN DRDC committee the DRD1 collaboration proposal has been fully approved by CERN in December 2023. To date, the collaboration consists of about 700 members from 157 institutes and 33 countries.

Within the new DRD1 collaboration, the FFN group (IKP in FZ Jülich, RU Bochum, and GSI) together with partners in the Jagiellonian University Krakow and IFIN-HH Bucharest, will carry out a research and development project for Straw Chamber technologies in hadron physics applications. One focus of this work package project is the development and optimization of a 4D+PID central tracker with track reconstruction in 3D-space, t0 track time extraction and dE/dx measurement for particle identification, combined with a very low material budget. The latter is essential for clean and background-suppressed particle tracking in hadron physics experiments in the GeV/c momentum region. Another topic is the development of small diameter straws for higher particle rate applications in hadron physics.

Outlook for 2024

We plan to test our online calibration prediction methodology in a real-time experimental setting during the next HADES beam time scheduled for Feb-Mar 2024. Afterwards, the study will be broadened for other detectors and generalized. Additionally, development of an AI-based tool for quick detection and classification of malfunctions in the detector's systems during the beam times is planned for 2024-2025 years. Furthermore, we will extend the PWA framework to proton-proton reaction channels, which are pertinent to the research areas highlighted in this report.

Selected publications of 2023

- [1] Esmail, W. et al., “KinFit: A Kinematic Fitting Package for Hadron Physics Experiments”, Computing and Sofware for Big Science 8, 3 (2024), DOI:10.1007/s41781-023-00112-x.
- [2] Ambats, I. et al., “Systematic study of $\pi^\pm$ p, $K^\pm$ p, pp, and p $^{-}$p forward elastic scattering from 3 to 6 GeV/c,” Nucl. Phys. D, 9(5), 1179, DOI:10.1103/PhysRevD.9.1179.
- [3] Abou Yassine, R. et al., “Investigation of the Σ^0 Production Mechanism in p (3.5 GeV)+p Collisions”, Eur. Phys. J. A 2024 in print. DOI:10.1140/epja/s10050-023-01214-1.
- [4] The 2021 ECFA (European Committee for Future Accelerators) detector research and development roadmap, https://cds.cern.ch/record/2784893.
- [5] DRD1 Extended R&D Proposal, Colaleo, Anna (Universitae INFN, Bari (IT)), Ropelewski, Leszek (CERN) et al., https:/cds.cern.ch/record/2885937.

6.2 CBM

Head: Prof. J. Ritman (GSI, RU-Bochum & FZ-Jülich)
Authors: D. Grzonka (FZ-Jülich, GSI), R. Kliemt (RU-Bochum), J.G. Messchendorp (GSI), D. Okropirdze (RU-Bochum). Ö. Penek (GSI), J. Ritman (GSI, RU-Bochum, FZ-Jülich), J. Taylor (GSI), V. Verhoven (GSI, Uni. zu Köln), P. Wintz (FZ-Jülich)

Highlights in 2023

Proposed Proton-Proton Program at CBM

Proton beams from SIS100 enables a hadron physics program complementary to the foreseen heavy-ion program with CBM. These beams impinging on a liquid hydrogen target enable systems with center-of-mass energies up to $\sqrt{s}=7.5$ GeV to be produced. The CBM detector acts as a suitable instrument to reconstruct (exclusively) the final state products from these reactions. In this context, the proton-proton studies with CBM at SIS100 will be a natural extension of the ongoing physics studies using proton and secondary pion beams with HADES at SIS18.

In order to develop an inspiring physics program with SIS100 protons, a one-day satellite event connected to the MESON2022 conference was organized in June 2023. This event will be followed-up by a dedicated workshop that will be held in Wuppertal in February 2024. Moreover, various Monte Carlo studies based on fast-simulation tools were performed to review the feasibility of some of the key reaction channels of interest. So far, we identified promising opportunities in the field of spectroscopy and structure with hyperons with strangeness $|S|=2,3$ and in the domain of near-threshold hidden- and open-charm production. The production rates of double and triple hyperons are expected to be very competitive with respect to other facilities. Together with a high-resolution charged-particle detector, such as provided by CBM, it would allow precision line-shape measurements of excited hyperons and it gives access to electromagnetic transition form factors of excited hyperons that have not been studied so far. Such measurements maybe a smoking gun revealing their exotic nature.

The near-threshold charm production can be exploited to study the charm-nucleon interaction which in turn gives access to the intrinsic charm contribution of the proton and to the emergent hadron mass contribution. The near-threshold production of hidden-charm vector mesons in proton-proton collisions, e.g., via reactions like $pp \to ppJ/\psi$ with dileptonic decays of the J/ψ, are of particular interest. Since the proton and the J/ψ do not share valence quarks, a pure gluonic exchange is expected to dominate and it is, albeit speculatively, possible to access gluonic gravitational form factors based on a hadroproduction scenario.

Assuming a cross section of ~1 nb for J/ψ production, a 6% branching fraction of J/ψ dileptonic decays, and 10^{10} to 10^{11} protons on target per 10 seconds (spill) one can expect about 1,100 to 11,000 reconstructed events with CBM per day, respectively. Figure 62 shows the reconstruction efficiency versus the proton beam momentum.

The p_t cuts in Figure 62 are used in heavy ion collisions and automatically imply a smaller reconstruction efficiency the higher the cut value is. A proton-proton collision program significantly improves the efficiency e.g., by up to a factor of ~6 for a lab momentum of 30 GeV/c compared to a CBM heavy ion program which has a 5% efficiency (Figure 62, black line, 30 GeV/c). Provided that the treatment of background is under control, it is possible to access the interactions of protons and J/ψ mesons by studying the differential cross section as a function of momentum transfer.

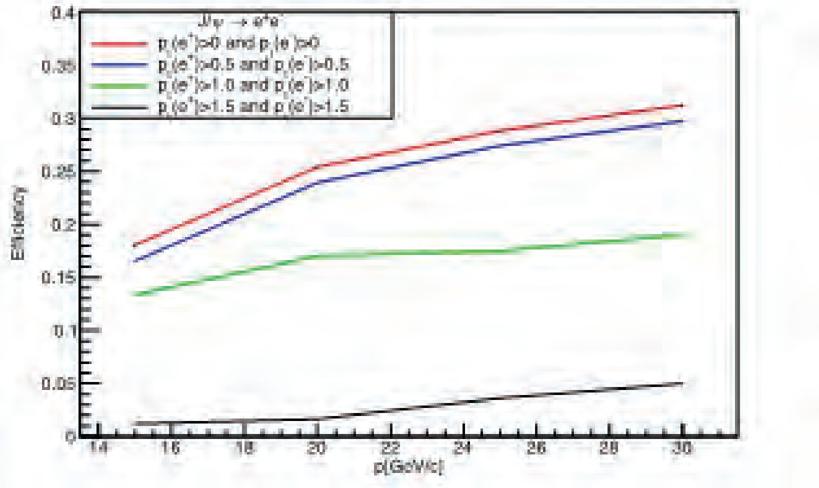

Figure 62. Signal reconstruction efficiency for the channel pp->ppJ/ψ for J/ψ->ee decays as a function of the lab momentum for the CBM detector using fast simulations (HepFastSim package). The different colors represent different p_t cuts i.e. cuts on the transverse momentum applied separately on the electrons and positrons.

Development for the FSD

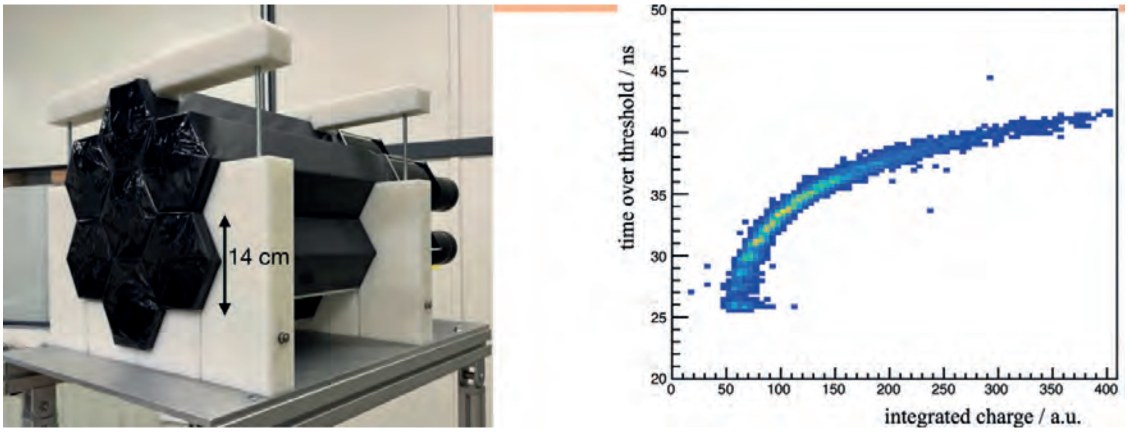

Figure 63. (left) Detector element with 7 hexagonal shaped scintillator modules. (right) Correlation between integrated signal charge and ToT-value achieved in first tests.

An extension of the Forward Spectator Detector (FSD), which will consist of a segmented plastic scintillator wall, by an additional neutron detector is considered. Neutron detection will improve the determination of collision centrality and reaction plane in heavy ion reactions and will be important for the analysis of various proton induced reaction channels. Directly downstream of the FSD it is planned to install an array of long plastic scintillator modules coupled to photomultipliers, thus providing a neutron detection efficiency of about 30%. In order to investigate the performance of such a detector component, two detector elements consisting of 7 scintillator modules each, have been prepared to be installed at mCBM for the test measurements in 2024, see Figure 63 (left). The scintillator modules have a hexagonal shape with a side length of about 14 cm and a length of 45 cm resulting in an area of about 1200 cm^2 for each detector element. One detector element will be positioned behind the TOF-detector of mCBM to correlate the particle tracks with the scintillator signals and the other element will be combined with FSD scintillator modules and placed close to the beam line.

Presently the read-out of the scintillator signals is being integrated into the CBM data acquisition system. The signal amplitude is determined by a time over threshold (ToT) method and first tests give a reasonable correlation between signal charge and ToT value as shown in Figure 63 (right).

Gas system for the TRD

The CBM Transition Radiation Detector (TRD) is essential to achieve strong background suppression for the identification of electrons/positrons at and above the GeV scale. The produced x-ray radiation is converted in a Xenon based gas detector. Our group has started to take over the task to build this gas system. A main design criterion is the very high level of pressure stability/regulation relative to the ambient atmospheric pressure over the large detector volume.

Outlook for 2024

The physics perspective with proton beams from SIS100 at CBM will be further developed in 2024. For instance, in February we are hosting a 1-week workshop on this topic at the University of Wuppertal.

Data will be taken with the FSD modules during the mCBM test measurements and will be used to determine the performance of the detector elements for neutron and charged particle detection. Those data will be compared to simulation studies. Based on the results a neutron detector will be designed for the full CBM detector as an extension of the FSD detector component.

6.3 PANDA

Head: Prof. J. Ritman (GSI, RU-Bochum & FZ-Jülich)
Authors: G. Perez-Andrade (FZ-Jülich, RU-Bochum), Tobias Stockmanns (FZ-Jülich),
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Highlights in 2023

Software

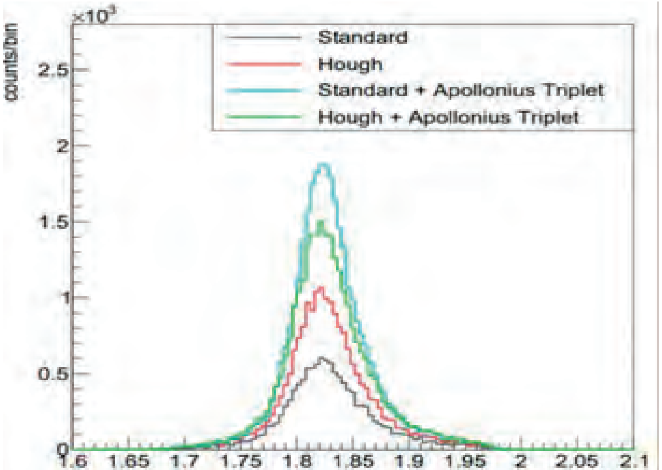

Figure 64. Reconstructed $\Xi(1820)^-$ with two primary track finders (Standard and Hough) and in combination with the newly developed secondary track finder (Apollonius Triplet).

One of the most challenging aspects in the reconstruction of the data of the future PANDA detector is the finding and fitting of tracks of charged particles in the solenoidal magnetic field of the barrel spectrometer. This task can be simplified by assuming that a track is coming from the known primary interaction point and many tracking algorithms have been developed for this purpose in PANDA. This works well for most physics cases but breaks down if one is studying hyperons, baryons with at least on open strange quark. The ground state of these particles can only decay via the week force which makes these particles quite long living and their decay products are displaced by several centimeters from the primary interaction point and the existing tracking algorithms can only poorly reconstruct these tracks.

Therefore, a new algorithm called the Apollonius-Triplet-Track Finder was developed focusing especially on tracks originating several centimeters away from the origin. The algorithm makes use of the special geometry of the Straw Tube Tracker (STT) with its densely packed drift tubes and the measurement of the drift times in each tube. To evaluate the performance of the new track finder in comparison with the existing ones the benchmark channel anti-pp -> $\Xi(1820)^-\Xi^+$ was selected which decays into one prompt kaon and 5 delayed protons and pions which makes it an ideal test case for secondary track finders. Figure 64 shows the change in the reconstructed $\Xi(1820)^-$ with the two primary track finders of PANDA and the improvement by combining them with the Apollonius Triplet Track Finder. One can clearly see the improvement of the reconstruction efficiency by using the secondary track finder. The best performance is achieved by using the Standard Track finder with the Apollonius Track finder. The full reconstruction efficiency could be improved by more than a factor 4, from 2.4% to 9.9%. This work was awarded the 2023 PANDA outstanding achievement award.

STT

The next step for the STT system will be to set up one complete STT hexagon sector with connected electronic readout system, gas and high voltage supply system. The system performance of spatial track resolution in 3D-space and particle identification (PID) by the particle specific energy-loss via a measurement of the straw analogue signal time-over-threshold will be determined and optimized. All single straws for the STT have been assembled and are available to be arranged and glued together into multi-layer sector modules. All components of the final electronic readout system, consisting of PASTTREC-ASIC front-end boards and TRB5c time readout boards, will be soon available. This joint project will be done together with partner groups at the Jagiellonian University and AGH in Krakow and the IFIN-HH institute in Bucharest.

KOALA

One prime goal of KOALA experiment is to measure the differential cross section of antiproton-proton elastic scattering, which will provide the normalization needed for PANDA. The concept of KOALA is to measure the (anti)proton-proton elastic scattering down to Coulomb region, therefore, the Coulomb scattering can be fixed to normalize the absolute luminosity. The KOALA experiment has been commissioned at COSY by measuring the proton-proton elastic scattering. The results of the commissioning clearly verified the experiment concept as well as the detector setup. Meanwhile the tests also showed the impact of finite target size and the beam imperfection, which limits to achieve the desired precision for KOALA and PANDA.

Recently, a working group has been built to investigate those challenges. One effort is being paid on the study of the cluster beam evaporation, which generates high vacuum background in the scattering chamber. Simultaneously, the influence on the measurement precision from the target thickness, variable beam profile as well as misalignment is being studied with KoalaSoft. In order to tolerate certain beam imperfection such as big profile or small misalignment, a larger forward detector has been proposed and implemented into the simulations.

Outlook for 2024

In the upcoming year, a dedicated event generator for investigating the impacts of target as well as beam on KOALA experiment will be developed. The simulation studies will provide required specifications for the design of a new cluster jet target for KOALA.

Selected publication of 2023

- [1] V. Abazov, et al., Hyperon signatures in the PANDA experiment at FAIR, https://arxiv.org/abs/2304.11977

6.4 Neutrino Physics

Head: Prof. Dr. L. Ludhova (FZ-Jülich, RWTH-Aachen)
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Highlights in 2023

Borexino

The Borexino experiment took data from May 2007 until October 2021 using a 280-ton liquid scintillator (LS). In 2023 its final CNO measurement was published [1] and selected as an Editors' Suggestion. The Correlated and Integrated Directionality (CID) method was applied, which relies on the detection of fast, sub-dominant Cherenkov light in a LS detector. The directional CNO measurement uses the complete Borexino data-taking period and was applied separately for Phase-I (2007-2021) and Phase-II+III (2011-2021). The zero-CNO hypothesis is rejected with a significance greater than 5σ, for the first time without any assumption on the backgrounds present in the detector. In particular, the analysis does not rely on any external constraint on the 210Bi contamination of the LS, a critical aspect in the spectral analysis approach used in the first CNO measurements. Moreover, the result obtained with the CID method can be used as an external constraint for the spectral analysis of the Phase-III data, the only dataset for which an independent ^{210}Bi constraint is available. The final and the most precise Borexino CNO measurement is R (CNO) = $6.7^{+1.2}_{-0.8}$ (stat. & syst.) counts per day/100 ton, disfavoring the zero-CNO hypothesis by 8σ C.L.

JUNO

The JUNO Experiment is a neutrino experiment under construction near Kaiping city in Southern China, with a planned completion in 2024. 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 52.5 km. JUNO has also a broad physics program addressing various topics in neutrino, particle, and astrophysics. In 2023, in a close collaboration with the INFN Milano group we published a collaboration paper about the JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos using solar neutrino spectroscopy. As a result, JUNO has a vast potential to exceed the precision of the existing Borexino measurement [2]. We are also involved in the JUNO antineutrino analysis, with focus on the JUNO sensitivity to geoneutrinos, studying different aspects of this analysis in a close collaboration with IHEP and Ferrara groups. We also provided the first JUNO simulation of the (α, n) background. We also work on the estimation of the JUNO NMO sensitivity with atmospheric neutrinos. To reach its goals, the JUNO detector requires a high level of radiopurity. To ensure this, the 18-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. We are responsible for building the calibration system of the OSIRIS detector with radioactive and LED sources. Two PhD students spent time on site working on the installation and commissioning of the OSIRIS detector and particularly on bringing to operation the calibration system.

Outlook for 2024

Borexino main analysis is completed. In 2024, we consider publishing a technical paper about the long-term stability of the Borexino detector, as a result of our studies of the systematic uncertainties in the solar neutrino analysis. Within JUNO, we will continue with the solar neutrino analysis. In particular, we will further apply our Borexino experience with the directional CID analysis with focus on the CNO solar neutrinos. In 2024, we will complete the analysis using the full simulation software. A dedicated collaboration paper is also planned. JUNO sensitivity to geoneutrinos is also to be finalized and a collaboration paper is to be prepared. We are also considering a dedicated technical paper about the (□□ n) background evaluation. We will also finalize the atmospheric neutrino studies and evaluate its publication. Additionally, we will work on the preparations for the detector commissioning, covering the topics as detector calibration, online event classification, and first data analysis.

Selected publications of 2023

- [1] D. Basilico et al., Final results of Borexino on CNO solar neutrinos, Phys. Rev. D 108 (2023) 102005.
- [2] A. Abusleme et al., JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos, J. Cos. Astro. Phys. 10 (2023) 022.

6.5 Polarized Atomic Beams

Head: Dr. R. Engels (FZ-Jülich)
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Highlights in 2023

A new method to generate hyperpolarization

Particles with a velocity v passing through a static, but oscillating magnetic field of two opposite coils experience in their system at rest an incoming radio-wave pulse that is monochromatic and coherent. The energy of the corresponding photons is $E_{Ph} = h \cdot v/\lambda$, where λ is defined due to the distance of the coils and, thus, the energy is tunable in a wide range from $E_0 \sim 10^{-7}$ and 10^{-12} eV. These photons can induce transitions within the hyperfine substates of atoms, molecules and their ions that can interfere with each other. By that the occupation numbers of the substates can be manipulated to produce an asymmetry far from thermal equilibrium, i.e., a large electron or nuclear polarization. Meanwhile, an international patent under the rules of the Patent Cooperation Treaty (PCT) was requested.

In the recent month the theoretical understanding of this method was developed further and several aspects that influence the simulations are investigated. Especially inhomogeneities of the magnetic field distribution, the particle distribution in the beam and the influence of the occupation numbers before the coils can have a huge impact on the theoretical predictions [1].

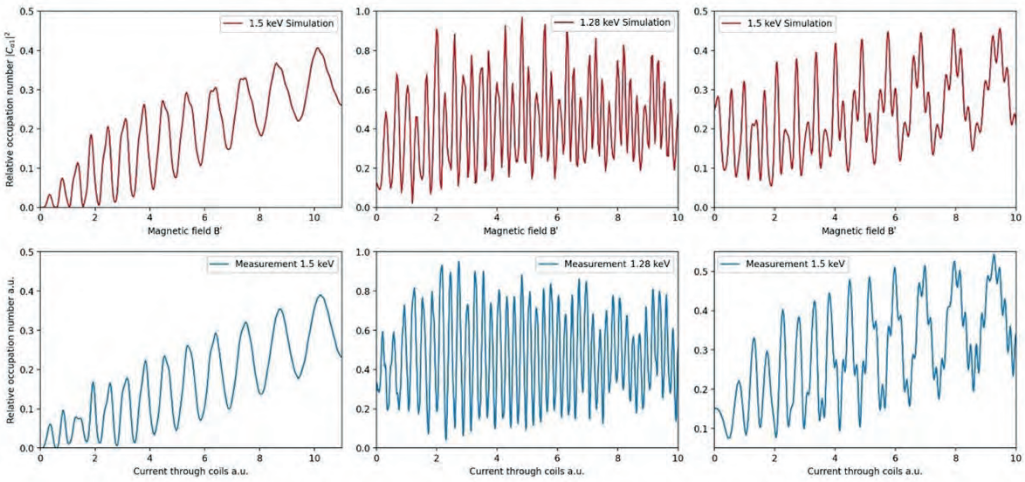

Figure 65. The theoretical predictions for the relative occupation number of the metastable hyperfine substate α1 (red) and the experimental results (blue) when a beam of metastable hydrogen atoms passes the opposite coils with different occupation numbers at the beginning, i.e. a.): $|c\beta 3|=1$, b.): $|c\alpha 2| = 0.5 = |c\beta_3|$ and c.): an unpolarized beam with $|ci| = 0.25$.

A polarized $^3He^+$ ion source

In principle, this method will be able to polarize many different kinds of ions even of heavy elements. As a first example we tried to polarize $^3He^+$ ions, because its hyperfine structure is very similar to the hydrogen atom besides the negative nuclear g-factor. During the last beam time at the cyclotron JULIC at FZJ an unpolarized beam of these ions was send through such a coil system, accelerated and the induced nuclear polarization was investigated with a nuclear reaction polarimeter normally used for polarized H-and D- beams. The data analysis is in progress.

Is amorphous carbon useful to coat a polarized storage-cell target at LHCb?

The SPIN@LHCb project is investigating the possible to implement a polarized at the LHCb detector at CERN. This target consists of a polarized atomic beam source and a T-shaped storage cell to store the incoming polarized atoms. Due to vacuum and beam transportation policies the standard coatings for storage cells are not allowed at LHC, but as a compromise amorphous carbon might be an option. For this material astrophysical observations show that most recombination mechanisms, the main reason for polarization losses, are obsolete. Corresponding measurements with such a coating prepared by P. Costa Pinto from CERN showed a very large recombination rate of more than ~95% that is produced due to radiation induced desorption by a large number of Lyman-α photons that stem from the dissociater of the ABS. Nevertheless, these measurements show although that the produced molecules kept about 2/3 of the original polarization of the atoms.

A Lamb-shift polarimeter for a pulsed H^-/D^- source

Until now Lamb-shift polarimeter are used for continuous polarized proton/deuteron beams or, in combination with an ionizer, for polarized atomic and molecular beams. In combination with the polarized ion source at COSY it could be shown that this type of polarimeter is even able to determine the nuclear polarization of pulsed beams of negatively charged ions. Here, the main issue is that a direct charge exchange from the negative ions into metastable hydrogen/deuterium atoms inside a cesium vapor cell with a strong magnetic field is possible without polarization loss. Until now, the negative ions were stripped in a helium gas cell and then transferred into metastable atoms by charge exchange with cesium vapor, but then the efficiency of the whole polarization measurement was not good enough to determine the polarization in a reasonable time.

Outlook for 2024

Until now only the behavior of metastable hydrogen and deuterium beams was investigated, because an existing Lamb-shift polarimeter allows to measure the induced polarization. In a next step this new technique will be tested with a beam of deuterium atoms in the 1S1/2 ground state like they are used to feed a tokamak or stellerator, because “polarized fuel” can potentially increase the energy output of such fusion reactors [2]. In this case the nuclear polarization can be measured with a nuclear-reaction polarimeter based on the known analyzing power of the d+d -> t+p reaction. The existing setup in Jülich allows a maximum beam energy of 6-7 keV and a beam intensity of a few µA. Therefore, the expected count rate in the detectors is just a few counts/h and, therefore, the necessary time for such an experiment will be months. In parallel a first test with a beam at 30 keV and a few mA at the Fusion Plasma Physics Department of the Centre for Energy Research in Hungary with the existing polarimeter is in preparation. As next, tests with existing fuel sources (40 keV, 4-40 A) at the DIII tokamak or at the University of Wisconsin are under discussion. In this case a new polarimeter must be designed, because the yet used foil targets must be replaced by a gas-jet target. Another interesting proof of this technique would be to demonstrate the nuclear polarization build-up in a slow beam of D_2 molecules at equal velocity (E_{beam} ~ 40 meV). After optimization of the setup these polarized molecules might be frozen on a cold surface inside a strong magnetic field to collect them again as polarized fuel for pellet injection into tokamaks like ITER. Further applications might be the production of polarized tracer for a better resolution of MRI scans in medicine. First discussions have started to pursue this with the Institute for Medical Imaging Physics (INM-4) and Structural Biochemistry (IBI-7) at FZ Jülich.

Selected publications of 2023

- [1] R. Engels et al.; A Universal Method to Generate Hyperpolarization in Beams and Samples, arxiv.org/abs/2311.05976.
- [2] C. Zheng et al.; First evidence of nuclear polarization effects in a laser-induced 3He fusion plasma, arxiv.org/abs/2310.04184.

6.6 JEDI

Head: Prof. J. Pretz (FZ-Jülich, RWTH-Aachen)
Authors: Achim Andres (FZ-Jülich, RWTH Aachen), Daoning Gu (GSI, RWTH Aachen), Volker Hejny (FZ-Jülich), Andro Kacharava (FZ-Jülich), Alexander Nass (FZ-Jülich), Jörg Pretz (FZ-Jülich, RWTH Aachen), Frank Rathmann (FZ-Jülich), Saad Siddique (GSI, RWTH Aachen), Max Vitz (FZ-Jülich, RWTH Aachen)

Highlights in 2023

Axion Searches

A paper on the search for axion/axion like particle (ALPs) at the Cooler Synchrotron COSY has been published in PRX [1]. The JEDI collaboration could for the first time establish a new complementary method to search for axion/ALPS. At storage rings especially the sensitivity on the axion-nucleon coupling via the so-called axion wind term is enhanced be several orders of magnitude compared to other experiments because of the high velocity of the deuterons. This method could be employed at other storage rings like the ESR or CRYRING. Although the data taking was planned as an engineering run with only a few days of physics data taking the JEDI result reaches similar sensitivity as other experiments and the result already appeared in the latest Review of Particle Physics [2].

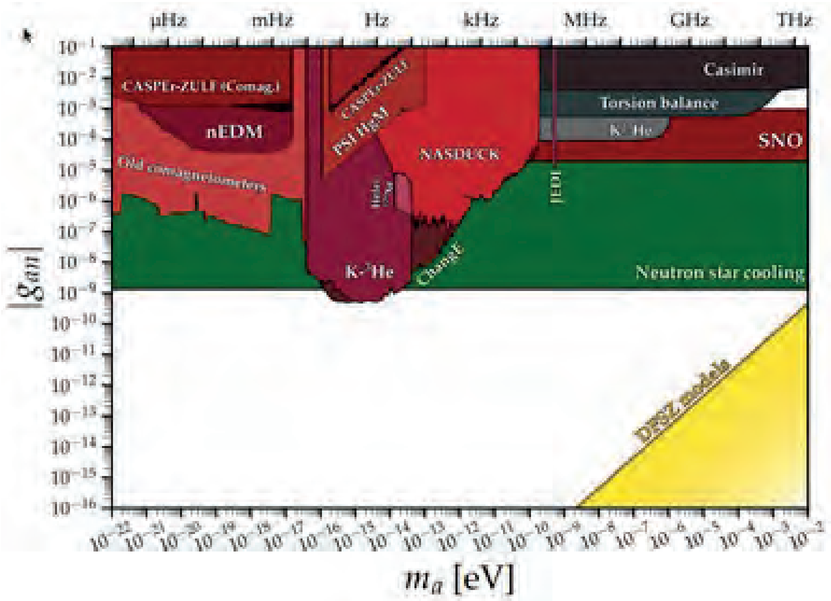

Figure 66. Limits on axion/ALP neutron coupling from the particle data group [2] including the recent result from the JEDI collaboration obtained at COSY [1]. Figure taken from https://pdg.lbl.gov/2023/reviews/rpp2022-rev-axions.pdf, Fig. 90.3.

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. These systematic effects are still under investigation. In addition, other effects like possible bias due the fitting procedure, varying spin coherence time during the data taking are investigated. In summer 2023 a beam time dedicated to systematic studies was performed. Analysis is still ongoing.

Pilot Bunch technique

In 2023 two papers [3,4] on the so-called pilot bunch method were published as preprints and sent to journals.

In the so-called pilot bunch method two bunches are stored in COSY. The Wien filter is gated off during the passage of one of the bunches, only the second bunch sees the Wien filter fields.

Design Study of a dedicated EDM ring

A proposal "Pathfinder Facility for a new class of PREcision STOrage rings (PRESTO)" was submitted as a "Research Infrastructure Concept Development" to the European Commission. The project was very well evaluated but due budget constraints the project was not financed. In Juelich the work concentrates on a new method to extract a beam using a pellet target from the storage ring a send it to a solid target for polarimetry. This method is essential to reduce systematic errors in the polarization measurement since the beam can be sampled randomly using the pellet technique.

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

Studies are going on to investigate the possibility of performing axion/ALP searches at the GSI storage rings. First results indicate that this seems to be difficult at the CRYRING because the low relativistic γ factor. It looks more favorable for the ESR.

Outlook for 2024

The main goal for 2024 is the finalization of the analysis of the deuteron EDM measurement at COSY.

Selected publications of 2023

- [1] S. Karanth et al., Phys. Rev. X 13, 031004 (2023).
- [2] R. L. Workman et al., PTEP 2022 (2022) 083C01, DOI:10.1093/ptep/ptac097.
- [3] J. Slim et al., Pilot bunch and co-magnetometry of polarized particles stored in a ring, arXiv.2309.06561.
- [4] N. N. Nikolaev, Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings, arXiv.2309.05080.

7. Research of the Theory Departments

Coordination: Prof. Dr. Hannah Elfner (Universität Frankfurt & GSI)
Author: Hannah Elfner, Gabriel Martínez-Pinedo

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

Students of Hannah Elfner collaborate with HADES to obtain constraints on the nuclear equation of state. In Fall 2023 another HFHF retreat took place, this time as a joint meeting with the European STRONG 2020 initiative and was successfully held in Catania, Italy with many contributions by early career researchers. A highlight of the year was the Hard Probes 2023 conference, which took place in March in Aschaffenburg and was co-organized by Elena Bratcovskaya. Renan Hirayama (HFHF PhD student in group of H. Elfner) won a flash talk with his poster on elliptic flow of dileptons in low energy heavy ion collisions as they are measured at GSI in Darmstadt.

The SFB 1245 “Nuclei: From Fundamental Interactions to Structure and Stars” with Almudena Arcones, Andreas Bauswein and Gabriel Martínez-Pinedo as Principal Investigators was extended for its third funding period by the Deutsche Forschungsgemeinschaft (DFG). The DFG also awarded funding for a new International Research Training Group (IRTG 2891) “Nuclear Photonics” with Gabriel Martínez-Pinedo as one of the PIs. Almudena Arcones has been appointed Max-Planck-Fellow at the Max-Planck Institute for Nuclear Physics in Heidelberg. Karlheinz Langanke has been appointed honorary member of the European Physical Society.

7.1 Hot and dense QCD matter

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

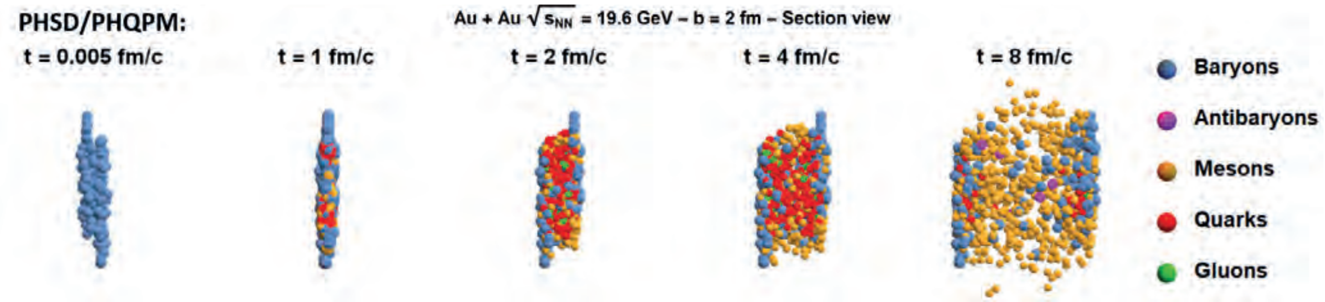

Figure 67. **Almost central gold-gold collision at intermediate beam energies simulated with PHSD/PHQPM. At early times a quark-gluon plasma forms which is later transformed to hadrons that reach the detector.**

The main goal of the theory groups working on hot and dense QCD matter is to understand the dynamical evolution of heavy-ion collisions over a broad range of beam energies. For the interpretation and prediction of experimental measurements, it is crucial to provide detailed calculations that connect observables to input from quantum chromodynamics (see Figure 67). Together with colleagues in Europe and international collaborators, sophisticated calculations based on relativistic hydrodynamics and transport theory are performed. Several transport approaches are continuously developed and applied by experimental collaborations and theory colleagues from all over the world. A review article that summarizes the main findings and open questions in the field of heavy-ion physics and meant as a good starting point for PhD students and people from other fields who are interested in the status of the field has been published by H. Elfner and B. Müller [1]. Moreover, other useful review addressing the physics of phase transitions in a non-perturbative regime studied by ab initio Lattice Field Theory methods and their application to heavy-ion physics has been published with participation of E. Bratkovskaya [2].

- [1] H. Elfner and B. Müller, The exploration of hot and dense nuclear matter: introduction to relativistic heavy-ion physics, J. Phys. G 50 (2023) no.10, 103001, DOI:10.1088/1361-6471/ace824
- [2] G. Aarts et al., Phase Transitions in Particle Physics : Results and Perspectives from Lattice Quantum Chromo-Dynamics Point, Prog. Part. Nucl. Phys. 133 (2023) 104070 [arXiv: 2301.04382 [hep-lat]]

Highlights in 2023

One of the main goals of heavy-ion research is the quest for structures in the phase diagram of strongly-interacting matter. Similar to water, that exists in different phases (fluid, ice and steam) the smallest constituents of matter form different structures depending on temperature and density. At high temperatures and small densities, theoretical calculations within quantum chromodynamics are performed on the lattice and concluded that there is a cross-over between the hadron gas and the quark-gluon plasma phase. At moderate temperatures and high densities as they are explored in low energy heavy-ion collisions as well as neutron star mergers, effective theory calculations suggest a first order phase transition. The potential critical endpoint motivates experimental efforts like the beam energy scan at the Relativistic Heavy Ion Collider (RHIC) and the FAIR CBM program.

The most important signature for the passage of matter through the critical endpoint is a change in correlation length and associated different fluctuations of conserved charges. Unfortunately, the system is very dynamic and many assumptions in theoretical calculations cannot be matched experimentally. For example, instead of the net baryon number fluctuations, only proton fluctuations can be measured. In [1] we have shown that the suggested mapping between protons and net baryons only works for small volumes (see Figure 68 below), while for larger volumes non-trivial dynamic scatterings play a role. Furthermore, the fate of fluctuations in the hadronic rescattering phase has been investigated in [2]. If the coupling of the critical mode to the baryons is large enough, the signature for criticality survives the rescattering as simulated within the SMASH hadronic transport approach.

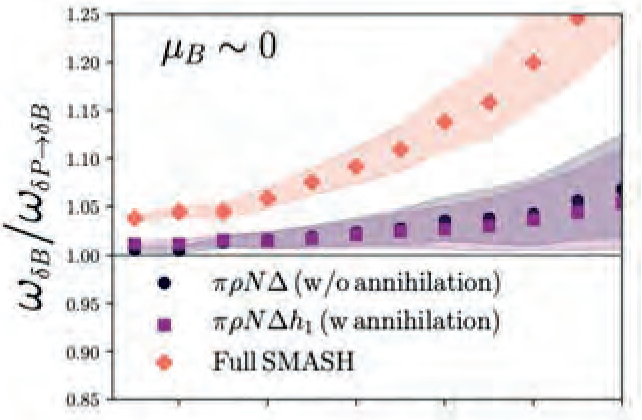

Figure 68. (part of Fig. 9 from [1]) Ratio of the scaled variance of baryons and baryons when mapped from the protons ωδB /ωδP -> δB as a function of the size of the subvolume. Three different systems with increasing number of degrees of freedom and interactions are shown.

The understanding of the mechanisms for the production of weakly bound clusters, such as a deuteron d, in heavy-ion reactions at mid-rapidity is presently one of the challenging problems which is also known as the “ice in a fire” puzzle. In Ref. [3] we have investigated the dynamical formation of deuterons within the parton-hadron quantum molecular dynamics (PHQMD) microscopic transport approach and advance two microscopic production mechanisms to describe deuterons in heavy-ion collisions from energies available at the GSI Schwerionensynchrotron (SIS) to those at the BNL Relativistic Heavy Ion Collider (RHIC): kinetic production by hadronic reactions and potential production by the attractive potential between nucleons. For the “kinetic” deuterons we have employed the full isospin decomposition of the various πNN<->πd, NNN<->Nd channels and took into account the finite-size properties of the deuteron by means of an excluded volume condition in coordinate space and by the projection onto the deuteron wave function in momentum space. We have found that considering the quantum nature of the deuteron in coordinate and momentum space reduces substantially the kinetic deuteron production in a dense medium as encountered in heavy-ion collisions. Adding the “potential” deuterons by applying an advanced minimum spanning tree (aMST) procedure, we have obtained good agreement with the available experimental data from SIS energies up to the top RHIC energy.

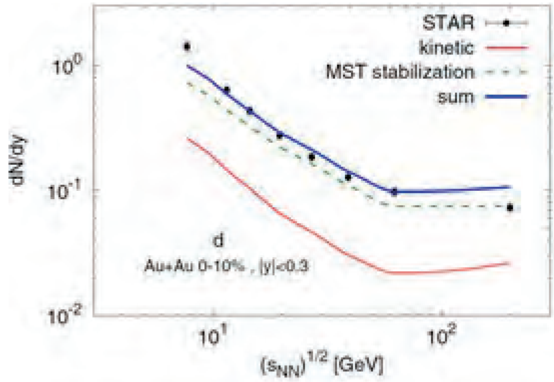

Figure 69. (Fig. 17 from [3]) The mid-rapidity |y| < 0.3 excitation function for dN/dy of deuterons as a function of $\sqrt{s_{NN}}$ for Au+Au 0–10% central collisions in comparison with the experimental data from the STAR collaboration. The lines indicate the different deuteron contributions: kinetic production with modelling of finite size effects in coordinate and momentum space (solid red), potential from MST with stabilization, i.e. advanced MST (dashed green), sum (blue).

Outlook for 2024

It is expected that we obtain first results from a Bayesian analysis of collective flow data from the HADES collaboration in comparison to SMASH with different parameter settings for the mean field. This will yield constraints for the equation of state of nuclear matter.

Also we expect to finalize the implementation of the 1st order phase transition in the microscopic off-shell PHSD transport approach and to obtain the first results on the ‘bulk’ observables and dilepton yields at FAIR energies where such transition might occur.

Selected publications of 2023

- [1] J. Hammelmann and H. Elfner, Impact of hadronic interactions and conservation laws on cumulants of conserved charges in a dynamical model, Phys. Rev. C 107 (2023) no.4, 044910, DOI:10.1103/PhysRevC.107.044910
- [2] J. Hammelmann, M. Bluhm, M. Nahrgang and H. Elfner, Fate of critical fluctuations in an interacting hadronic medium using maximum entropy distributions [arXiv:2310.06636 [nucl-th]].
- [3] G. Coci et al., Dynamical mechanisms for deuteron production at mid-rapidity in relativistic heavy-ion collisions from energies available at the GSI Schwerionensynchrotron to those at the BNL Relativistic Heavy Ion Collider, Phys. Rev. C 108 (2023) 1, 01490 [arXiv:22303.02279 [nucl-th]].

7.2 Hadron physics and QCD

Head: Matthias F. M. Lutz (GSI)
Authors: M. F. M. Lutz, 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

Low energy constraints from Lattice QCD

Low-energy constants (LEC) in the chiral Lagrangian are the bridge from Lattice QCD data to chiral perturbation theory. The knowledge of the latter allows systematic coupled-channel studies of the Goldstone boson scattering off the baryon octet and decuplet states at the physical point in a sustainable fashion. Owing to the nature of the chiral Lagrangian a large class of the LEC can be determined from QCD in terms of the quark-mass dependence of hadron masses. In our recent work [1] we performed an analysis of Lattice QCD data on baryon octet and decuplet masses. The relevant set of LEC are adjusted to describe baryon masses on a large set of ensembles from the Coordinated Lattice Simulations (CLS) Consortium. We consider finite-box and discretization effects. The set is successfully compared against previous Lattice QCD data from ensembles generated with distinct QCD actions by the ETMC, QCDSF-UKQCD and HSC groups. Discretization effects are modelled by the use of action and lattice-scale dependent leading orders LEC, where uniform values are imposed in the limit of vanishing lattice scales. From the CLS data set we extract a pion-nucleon sigma term of 58.7(1.2) MeV, compatible with its empirical value. At the same time, a rather large strangeness content of the nucleon was obtained.

While the results demonstrate the feasibility of the extraction of large classes of LEC from Lattice QCD data, our predictions have to be taken with grains of salt. We identified specific lattice ensembles from CLS, which are in tension with such global chiral extrapolations. It would be important to further improve and extend the data set, in particular for ensembles with identical up, down and strange quark masses, but along the line of fixed strange-quark masses. Most troublesome appear current ensembles at small pion masses for which it may be difficult to reach large enough Euclidean time separation at which masses can be extracted from correlator data unambiguously. We already see challenges for ensembles with pion masses of about 200 MeV. It was pointed out that the role of the decuplet states is of utmost importance. Due to loop contributions of the decuplet states, we expect a non-trivial and difficult-to-control volume dependence in the correlators as measured by Lattice QCD groups. The data set on the baryon decuplet masses may not be sufficient in quality and quantity yet to faithfully determine the set of LEC that are required for studies of coupled-channel systems of mesons and baryons. Given our setup we are currently unable to connect to lattice data on ensembles with physical pion masses. Here ensembles with smaller volumes may be more easily connected to EFT computations simply because their decuplet states are characterized by fewer energy levels as compared to their large-volume pendants.

An evolutionary algorithm for HPC clusters

Any amplitude analysis of coupled-channel scattering data, the main focus of our department, faces strong non-linear behavior as soon as realistic forces are used. Conventional gradient-based algorithm are not well suited for such systems. Therefore it is important to develop high-performance computing (HPC) tools based more suitable algorithms.

Many challenges of today's science are parametric optimization problems that are extremely complex and computationally intensive to calculate. At the same time, the hardware for high-performance computing is becoming increasingly powerful. Geneva is a framework for parallel optimization of large-scale problems with highly nonlinear chisquare surfaces in grid and cloud environments. To harness the immense computing power of high-performance computing clusters, we have developed a new networking component for Geneva—the so-called MPI Consumer—which makes Geneva suitable for HPC. Geneva is most prominent for its evolutionary algorithm, which requires repeatedly evaluating a user-defined cost function. The MPI Consumer parallelizes the computation of the candidate solutions' cost functions by sending them to cluster nodes. By using an advanced multithreading mechanism on the master node and by using asynchronous requests on the worker nodes, the MPI Consumer is highly scalable. Additionally, it provides fault tolerance, which is usually not the case for MPI programs but becomes increasingly important for HPC. Moreover, the MPI Consumer offers a framework for the intuitive implementation of fine-grained parallelization of the cost function. Since the MPI Consumer conforms to the standard paradigm of HPC programs, it vastly improves Geneva's user-friendliness on HPC clusters. Geneva—including the novel MPI Consumer—is publicly available as an open source project on GitHub (https://github.com/gemfony/geneva). We succeeded to run our MPI Consumer on the batch farm at GSI with about 3000 MPI ranks.

Exotic states with heavy quarks

Two of the first unexpected states discovered at the B-factories were the $D_{s0}^*(2317)$ and the $D_{s1}(2460)$ with a heavy charm and a strange (anti)quark. Unlike quark-models suggest, these hadrons appear as QCD bound-states below the D K and D^*K thresholds respectively and there are indications that they are best interpreted as meson molecules. Given their enigmatic role, the intriguing question whether QCD bound states with the same quantum numbers can also be found in the B_s spectrum arises. In [3] we studied the $J^P=0^+$ and 1^+ B_s ground states on a large set of CLS ensembles with different pion and kaon masses and various lattice volumes. The resulting prediction of the bound-state masses of the lowest positive parity states with a full uncertainty estimate is now awaiting to be confronted with future experimental results, which might be obtained by Belle II or LHCb. In the same publication, we also performed a comprehensive study of the systematic uncertainties in the Lattice QCD determination of bound-state candidates with two heavy (anti)quarks, where Lattice QCD results previously received a lot of attention. This resulted in a prediction of a fairly-deeply bound anti-b anti-bud tetraquark and a somewhat shallow bound anti-b/anti-bus state - fully consistent with previous Lattice QCD determinations but with much more thoroughly explored systematic uncertainties. Our results also show that the use of Non-Relativsitic QCD commonly used for the bottom quarks now limits the uncertainty on such predictions.

Outlook for 2024

For 2024, we plan to focus on scattering observables in open-charm and meson-baryon systems. For open charm systems, we will 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.

Selected publications of 2023

- [1] Lutz, Matthias F. M. , Guo, Xiao-Yu , Heo, Yonggoo: Low-energy constants in the chiral Lagrangian with baryon octet and decuplet fields from Lattice QCD data on CLS ensembles. Eur. Phys. J. C 83 (2023) 5, 440.
- [2] Weßner, Jonas, Berlich, Rüdiger, Schwartz, Kilian, Lutz, Matthias F.M.: Parametric Optimization on HPC Clusters with Geneva. Comput. Softw. Big Sci. 7 (2023) 1.
- [3] Hudspith, R.J., Mohler, D.: Exotic tetraquark states with two quarks and $J^P=0^+$ and 1^+ B_s states in a nonperturbatively tuned lattice NRQCD setup. Phys. Rev. D 107 (2023) 11, 114510.

7.3 Nuclear astrophysics and structure

Head: Prof. Dr. Gabriel Martínez-Pinedo (Technische Universität Darmstadt & GSI)
Authors: Andreas Bauswein, 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 2023

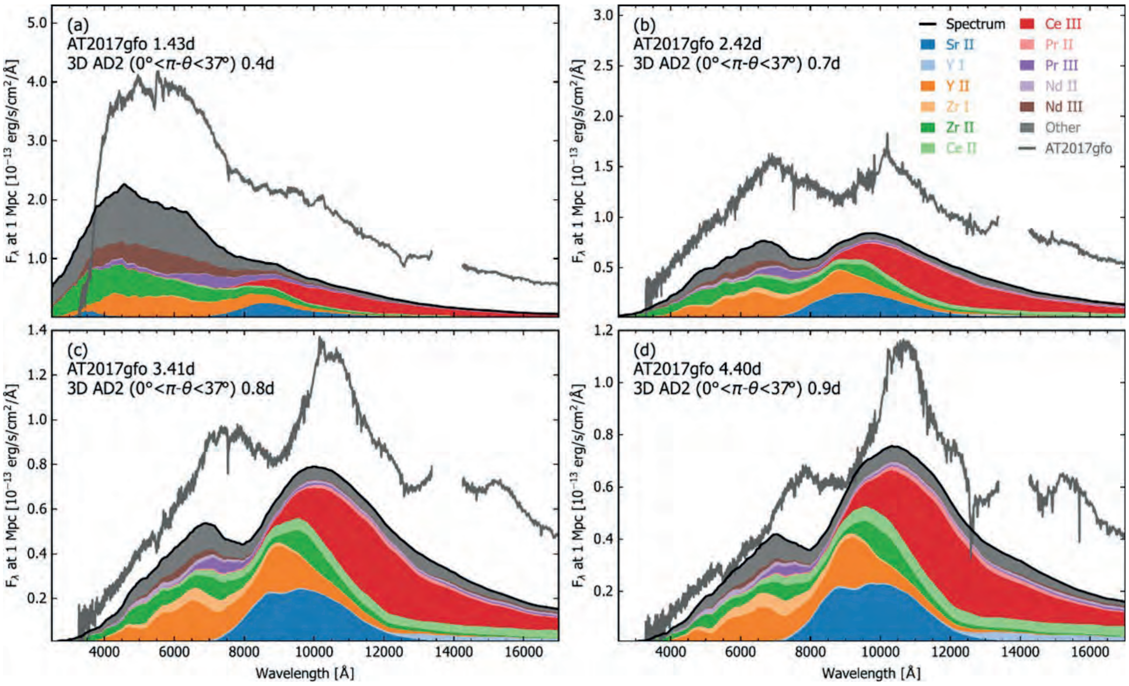

Figure 70. Time series of spectra emitted in the polar direction of a 3D kilonova model compared to the spectra of AT2017gfo. The area under the spectra has been colored by the emitting atomic species of the last interactions of the emerging photons. Adapted from L. J. Shingles, et al, Astrophys. J. Lett. 954, L41 (2023).

Significant progress has been done in the description of the ejecta from neutron star mergers, which produce heavy elements through the rapid neutron capture process (r-process). A major challenge for numerical models is the fact that matter gets unbound on different time scales by different physical mechanisms (e.g. dynamical ejection, neutrino driven winds, viscous heating), which may contribute comparable amounts of ejecta. Hence, for a reliable description of nucleosynthetic yields it is important to consistently consider all mass ejection channels and combine their respective production of heavy elements. In this regard, Reference [O. Just et al., The Astrophysical Journal Letters 951, L12 (2023)] takes an important step by modeling all ejection processes and computing the r-process nucleosynthesis consistently. The study focuses on mergers with intermediate remnant lifetimes, i.e. delay times until the central object collapses to a black hole after merging, of about a few 100 milliseconds. The total abundance distribution of heavy elements follows roughly the solar distribution but features some under-production of elments with mass number A>140. This tentatively suggests that systems with intermediate remnant life times of that order may not be the most frequent binary neutron star merger systems since otherwise the observed solar abundance pattern was not reproduced. An approximate estimate of the electromagnetic counterpart (kilonova) shows a good agreement with the observed kilonova AT2017gfo associated with the neutron star merger GW170817.

Regarding the kilonova emission, we have established a full modeling pipeline starting from hydrodynamical merger simulations, involving detailed nuclear network calculations, and feeding those data in radiation transfer codes. Employing such realistic input data in three dimensions represents a novelty and appears to be indispensable for an advanced and trustworthy description of kilonovae as these new studies clearly show that more approximate descriptions of e.g. the density profile fail to fully reproduce the complexity of the electromagnetic emission. These works have been put forward in Ref. [C. Collins et al., Monthly Notices of the Royal Astronomical Society 521, 1858]. Another major improvement is the inclusion of a line-by-line treatment of atomic transitions in the radiative transfer calculations of the kilonova [L. Shingles et al., The Astrophysical Journal Letters 954, L41 (2023)]. The consideration of several million atomic lines is computationally very challenging but is required to connect certain spectral features with individual elements. This new modeling pipeline allows to include time-dependent and local abundance and heating data of the ejecta. The agreement with the spectral properties of the kilonova AT2017gfo is remarkable considering that the input model was not tune in any way but represents a fully self-consistent merger simulation (neglecting late-time ejecta for these very first explorative studies.)

These studies highlight the importance of accurate line opacities for kilonova spectral modelling. Aiming to develop a database of calibrated kilonova opacities we have computed opacities for single and double ionized neodymium and uranium [A. Flörs et al., Monthly Notices of the Royal Astronomical Society 524, 3083 (2023)]. The calculations show that Actinides may have substantially larger opacities than Lanthanides and consequently the calculations are being extended to include all Lanthanides and Actinides.

We have also been involved in a re-analysis of the spectra of AT2017gfo, which suggests that the outflow occurred in a very spherical manner, i.e. with velocities along and perpendicular to the line of sight being in very close to each other [A. Sneppen et al., Nature, 614, 436 (2023)]. This result came as a surprise since most numerical merger models feature a certain asphericity of the ejecta albeit the analysis is not in contradiction with current models. The method laid out in this study yields an independent measure of the luminosity distance of the kilonoave, which is a promsing spin-off with the prospect of better determining the Hubble constant in the future through such type of measurements.

The group has also worked on understanding the impact of pions in neutron star mergers. Pions have been neglected in previous numerical simulations of neutron star mergers and their observables. The study [V. Vijayan et al., Physical Review D 108, 023020 (2023)] revealed that pins may have a sizable impact on for instance the gravitational-wave signal, the black-hole formation and the mass ejection and thus kilonova.

Another study was devoted to a detailed analysis of thermal effects of hybrid equations of state, i.e. models with a phase transition to deconfined quark matter, I the context of neutron star mergers and the gravitational-wave emission [S. Blacker et al., Physical Review D 108, 063032 (2023)]. The work showed that in comparison to purely baryonic matter, the temperature dependent phase boundaries of the hadron-quark phase transition introduce a very rich phenomenology, which is reflected the the gravitational-wave signal

We also finalized a work investigating the impact of nuclear uncertainties on r-process nucleosynthesis in neutron star mergers [Kullmann et al., Monthly Notices of the Royal Astronomical Society 523, 2551 (2023)]. Another paper considered compact dark objects in neutron star mergers and concluded that such particular models of Dark Matter might be detectable with gravitational-wave detectors under optimistic assumptions [Bauswein et al., Physical Review D 107, 083002 (2023)]. We also studied gravitational wave emission from mergers of main-sequence stars and during the common envelope phase [Moran-Fraile et al., Astronomy & Astrophysics 672, A9 (2023)].

Neutrino fast flavor instability is expected to be ubiquitous in core-collapse supernova and neutron star mergers. It rapidly shuffles neutrino flavor in a way that could impact the explosion mechanism, neutrino signals, mass outflows, and nucleosynthesis. Simulating the underlying quantum kinetics equations is very challenging and prone to numerical errors. Based on realistic spherically symmetric supernova models we have shown that collisional instabilities generally exist around the neutrinosphere during the supernova accretion and postaccretion phase [Xiong et al, Phys. Rev. D 107, 083016 (2023)].

Outlook for 2024

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 for 2023

- A. Sneppen, D. Watson, A. Bauswein, O. Just, R. Kotak, E. Nakar, D. Poznanski, and S. Sim, Spherical Symmetry in the Kilonova AT2017gfo/GW170817, Nature 614, 7948 (2023).
- O. Just, V. Vijayan, Z. Xiong, S. Goriely, T. Soultanis, A. Bauswein, J. Guilet, H.-T. Janka, and G. Martínez-Pinedo, End-to-End Kilonova Models of Neutron Star Mergers with Delayed Black Hole Formation, Astrophysical Journal Letters 951, L12 (2023). DOI:10.3847/2041-8213/acdad2
- L. J. Shingles, C. E. Collins, V. Vijayan, A. Flörs, O. Just, G. Leck, Z. Xiong, A. Bauswein, G. Martínez-Pinedo, and S. A. Sim, Self-Consistent 3D Radiative Transfer for Kilonovae: Directional Spectra from Merger Simulations, Astrophys. Journal Letters 954, L41 (2023).
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- V. Vijayan, N. Rahman, A. Bauswein, G. Martínez-Pinedo, and I. L. Arbina, Impact of Pions on Binary Neutron Star Mergers, Phys. Rev. D 108, 023020 (2023).

8. Collaborations & cooperations

8.1 Helmholtz Research Academy HESSE for FAIR (HFHF)

Head: Prof. Dr. Thomas Aumann (TU Darmstadt & GSI)
Author: Frank Nerling

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 2023

A highlight in 2023 was the organization of the 11th edition of the international Symposium NuSYM23, covering a broad spectrum of topics reflecting a large number of physics subjects supported and worked on within our HFHF Academy. The event was hosted at GSI Darmstadt [*], supported by HFHF and a number of HFHF PIs were involved in the local organization. More than 100 leading scientists from research centers and universities all over the world participated in this conference at GSI/FAIR. For a week, the world leading experts addressed experimental and theoretical investigations of the equation-of-state of asymmetric nuclear matter, including efforts in nuclear structure, nuclear reactions and heavy-ion collisions as well as in astrophysical observations of compact stars and associated phenomena. Implications of gravitational-wave signals, soft X-rays, astroparticle physics and neutrino observations were discussed as well.

[*] NuSYM23, “11th International Symposium on Nuclear Symmetry Energy”, Sep 18 – 22, 2023, GSI Darmstadt, Germany, for details see: https://indico.gsi.de/event/17017/overview.

HFHF events in 2023 (organized or supported by HFHF)

HARD PROBES 2023, “11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions” Organizers, among others: A. Andronic (co-chair), R. Averbeck (co-chair), E. Bratkovskaya, T. Galatyuk, S. Masciocchi (co-chair), Lorenz von Smekal, March 26 – 31, 2023, Aschaffenburg, Germany

ISPUN23, “International Symposium on Physics of Unstable Nuclei 2023”, Organizers: L.X. Chung, P.V. Cuong, P.N. Dong, M. Lebois, A. Obertelli, May 4 – 8, 2023, Phu Quoc Island, Vietnam

NuSym23, “11th International Symposium on Nuclear Symmetry Energy”, Organizers, among others: A. Le Fevre (Chair), Y. Leifels (Chair), T. Aumann, H. Elfner, T. Galatyuk, A. Schwenk, J. Stroth, September 18 – 22, 2023, Darmstadt, Germany

QFS-RB 2023, “5th International Workshop on Quasi-Free Scattering with Radioactive-Ion Beams 2023”, Organizers: M. Petri (Chair), T. Aumann (Chair), C. Bertulani, D. Cortina, A. Obertelli, S. Paschalis, T. Uesaka, October 1 – 6, 2023, Lefkada, Greece.

Selected publications of 2023

- [1] P. Bicudo, N. Cardoso, L. Mueller and M. Wagner, “Study of I = 0 bottomonium bound states and resonances in S, P, D, and F waves with lattice QCD static-static-light-light potentials”, Phys. Rev. D 107 (2023) 9, 094515, DOI:10.1103/PhysRevD.107.094515
- [2] J. Bernhardt, C. S. Fischer and P. Isserstedt, “Finite-volume effects in baryon number fluctuations around the QCD critical endpoint”, Phys. Lett. B 841, 137908, DOI:10.1016/ j.physletb.2023.137908
- [3] T. Reichert, A. Kittiratpattana, P. Li, J. Steinheimer and M. Bleicher, “Probing system size dependence at high baryon density by systematic comparison of Ag+Ag and Au+Au reactions at 1.23A GeV”, J. Phys. G 50 (2023) 2, 025104, DOI:10.1088/1361-6471/acaffa
- [4] Y. Kondo, et al., “First observation of 28O”, Nature 620 (2023) 965, DOI:10.1038/s41586-023-06352-6
- [5] H. Elfner and B. Müller, “The exploration of hot and dense nuclear matter: introduction to relativistic heavy-ion physics”, J. Phys. G 50 (2023) 10, 103001, DOI:10.1088/1361-6471/ace824
- [6] P. Jiang, K. Götzen, R. Kliemt, F. Nerling and K. Peters, “Deep machine learning for the PANDA software trigger”, Eur. Phys. J. C 83 (2023) 4, 337, DOI:10.1140/epjc/ s10052-023-11494-y

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

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

The GSI Helmholtzzentrum für Schwerionenforschung GmbH and its accelerator Facility for Anti-proton and Ion Research (FAIR) provide an excellent environment for doctoral research and structured doctoral training. In strong cooperation with its partner universities, young researchers are prepared for future careers inside and outside of academia and science. A key building block in this environment is the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe) at GSI-FAIR.

HGS-HIRe conducts structured doctoral training in all research fields of GSI and FAIR since more than 15 years. In addition to a variety of educational measures, the graduate school provides individual support as primary contact and care center for doctoral researchers in its program. By the end of 2023, more than 360 doctoral students, who conduct their research on GSI-FAIR related topics, are registered as participants in the HGS-HIRe program. 49 of them have been newly accepted for participation in the program of HGS-HIRe during 2023, 47 doctoral researchers affiliated with HGS-HIRe finished successfully their doctoral projects in 2023. The governance structure of the graduate school, fully implemented by the end of 2022 to better adjust to the organizational structure of GSI-FAIR, including the HGS-HIRe Administrative Office and the HGS-HIRe Management Board as well as the HGS-HIRe Application Review Committee has been proved highly efficient in the daily work of the graduate school in 2023.

After the challenging impact of the COVID-19 pandemic on the HGS-HIRe program in the previous years, the significant ease of the situation over the year 2023 allowed for a continued resumption of the graduate school's program activities. Compared to 2022, this particularly led to a further increase in the demand for individual travel funds by the HGS-HIRe participants due to steadily enhanced participation in conferences and workshops. Furthermore, the eased situation in 2023 allowed for more residential face-to-face program elements seconded by HGS-HIRe online events as established during the previous years of the pandemic. The following residential face-to-face training events, organized and offered by HGS-HIRe in 2023, are particularly worth mentioning:

- Joint RS-APS & HGS-HIRe Lecture Week on APPA Research at FAIR: From Fundamentals to Applications – a scientific training event at the Helmholtz Institute in Jena in February/March
- HGS-HIRe Power Week on Machine Learning in Schmitten/Taunus in July – a workshop with introductory lectures, use cases and a strong focus on hands-on sessions; this scientific training course was a follow-up of a very successful Participant Education Project on this topic in the previous year
- International Summer Student Program at GSI-FAIR from July to September – a training event for graduated students from GSI-FAIR partner countries, planned, organized and conducted in cooperation with a local team at GSI-FAIR
- Joint HGS-HIRe & SFB-TR 211 Lecture Week on Critical Phenomena in Strong-Interaction Matter – a scientific training event in Rauischholzhausen near Gießen in October
- HGS-HIRe Power Week on Silicon Pixel Detectors – a workshop in the HGS-HIRe power week format with strong focus on hands-on training in Rauischholzhausen in November

In its established and proven transferable skills training program, HGS-HIRe was able to offer a similarly high number of training events in 2023 as in the previous year. Altogether, in 2023 ten interactive transferable skills courses as part of an integrated series of courses, covering beginner and advanced courses, with a total of more than 220 participants have been organized and conducted by HGS-HIRe together with the experienced trainer team from Great Britain. The courses were organized and offered as residential face-to-face courses and as online courses. As in previous years, it was possible to attract doctoral researchers from other Helmholtz Graduate and Research Schools to attend these courses, leading to a more interdisciplinary learning environment and group structure in the courses and, moreover, an ongoing strengthening of a Helmholtz-wide network.

DOI:10.15120/GSI-2024-00500

Moreover, the HGS-HIRe information and supervision concepts including individual thesis advisory committees and online formats developed by HGS-HIRe to enable various contact and care offers have sucessfully been continued. In particular, the following supporting information and training events complemented the program offers in 2023:

- HGS-HIRe Perspectives – an event series that addresses career opportunities particularly outside the academic sector, and that brings together current HGS-HIRe participants and professionals from applied science or industry who graduated in natural science
- Quarterly HGS-HIRe Information & Contact Sessions for participants
- HEPTrepreneurs episodes by HEPTech in collaboration with the Technology Transfer (TT) Divisions at GSI-FAIR and CERN
- Helmholtz Young Entrepreneurs in Science workshops and various event offers by the Helmholtz Open Science Office

Last but not least, HGS-HIRe provided its information platform for the HGS-HIRe participants on additional advisory offers and services at GSI-FAIR and the partner universities as well as internal and external training events and course offers within, e.g., the Helmholtz community. Among these, external residential and online 'power weeks', i.e. training events on more specialized scientific and technical aspects and methods, as the Helmholtz Incubator Summer Academy, the Helmholtz GPU Hackathon 2023, 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 2023.

In summary, enabled by the ending of severe restrictions of the pandemic situation in 2023, HGS-HIRe has enhanced its efforts to further strengthen its structured program offers – including more residential face-to-face training events seconded by online courses and supportive information events. In 2023, the potential of stronger cooperation within the Helmholtz community to enhance the program of the school has been continued to be explored. It became apparent that this development, started in the previous years under a pandemic situation, has a positive impact on the HGS-HIRe program. Combinations of established online offers and re-established residential face-to-face training events have been successfully realized in 2023 and have been planned for 2024 to continue to offer a broad and attractive program for young researchers in the GSI-FAIR research and training environment.

8.3 ExtreMe Matter Institute EMMI

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

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)

Activities in 2023

EMMI events in 2023

EMMI Workshop "Effective field theories for nuclei and nuclear matter", Organizers: H.-W. Hammer, K. Hebeler, G. Martínez-Pinedo, T. Neff, A. Schwenk, January 15-23, 2023, Hirschegg, Austria

EMMI Workshop "4th Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC", Organizers: F. Bellini, S. Bufalino, J. Schaffner-Bielich, B. Dönigus, February 13-17, 2023, Bologna, Italy

ECT*-EMMI/GSI Workshop "Nuclear and particle physics on a quantum computer: Where do we stand now?", Organizers: A. Bazavov, Z. Davoudi, D. Lee, A. Roggero, June 5-9, 2023, Trento, Italy

ECT*-EMMI/GSI Workshop "Machine Learning for Lattice Field Theory and Beyond", Organizers: G. Aarts, D. Bachtis, D. Hackett, B. Lucini, P. Shanahan, June 26-30, 2023, Trento, Italy

EMMI Workshop "Bound states and particle interactions in the 21st century", Organizers: P. Camerini, B. Dönigus, R. Lea, J. Mares, S. Piano, July 3-6, 2023, Trieste, Italy

EMMI Physics Day, Organizers: K. Blaum, P. Braun-Munzinger, C. Ewerz, July 17, 2023, Darmstadt, Germany

EMMI RRTF "Direct-Photon Puzzle", Organizers: A. Marin, K. Reygers, J. Stachel, July 24-27, 2023, Heidelberg, Germany

EMMI Workshop "Functional Methods in Strongly Correlated Systems (FUNSCS2023)", Organizers: M. Buballa, F. Rennecke, N. Wink, September 10-15, 2023, Hirschegg, Austria

EMMI Workshop "Forward Physics in ALICE 3", Organizers: P. Lebiedowicz, R. Schicker, M. Völkl, October 18-20, 2023, Heidelberg, Germany

EMMI Collaboration Meeting "Towards a Vacuum Birefringence Experiment at the Helmholtz International Beamline for Extreme Fields", Organizers: H. Gies, F. Karbstein, G. Paulus, M. Zepf, October 26-28, 2023, Jena, Germany

EMMI RRTF "Fluctuations and Correlations of Conserved Charges: Challenges and Perspectives", Organizers: A. Rustamov, V. Koch, K. Redlich, J. Stachel, J. Stroth, N. Xu, November 6-10, 2023, Darmstadt, Germany

9. Accelerator Operations and Development

Head: Dr. Ralph Aßmann

9.1 Executive summary of Business Area Accelerator Operations and Development

Authors: Ralph Aßmann, Udo Weinrich

The Business Area "Accelerator Operations and Development" has completed a successful year 2023 during which several highlight results were achieved, summarized in this yearly report by the various responsible scientists.

In September 2023 the business area ACC was renamed from "Accelerator Operations" to "Accelerator Operations and Development". This change is linked to the fact that Ralph Aßmann took over as Head of the Business Area. Udo Weinrich, who served that position ad interim for a period of 2 1/2 years, acts now as deputy head.

ACC successfully finished the long shutdown period during which important maintenance work and repairs were executed. The final shutdown activities focused on the ESR electron cooler - which was compromised by the presence of asbestos and synthetic mineral fibres – and were finished before the end of the year. All ESR vacuum sectors were vented for the repair work and needed to be baked out again. The work on the ESR turned out to be highly beneficial as the final vacuum status was significantly improved. At the extraction level of 4 MeV/u in the ESR, the beam had the longest ever measured beam lifetime, a direct benefit also for the HITRAP beam commissioning.

Towards the end of the year 2023 an extensive engineering run took place. Newly developed beam patterns for the user run 2024 were tested and optimized for quality. Also, in parallel one PAC rated experiment at the CRYRING took place. Another focus of the engineering run was to train the operators and to progress on different machine studies and developments. Those studies aim for achieving improved operational performance of the existing GSI accelerators and for testing new components for the FAIR accelerator and experimental sections. Very successful results could be achieved on increasing the uranium beam intensities, on optimizing the spill structure (improved efficiency for data taking), on demonstrating a pulsed UNILAC gas stripper with nitrogen beam and on various other topics. Finally, also the prototype accelerator module for a possible future cw ion linac ("cw-advanced demonstrator") succeeded in accelerating He-ions up to 3.1 MeV/u.

The yearly Beamtime Retreat took place in September 2023. This workshop was organized as an in presence meeting for two days at the Achat Hotel Offenbach. The retreat was again a very fruitful platform for exchange between accelerator and experiment experts and a common discussion. The focus was on the different activities of the upcoming year 2024. One major result was that integration aspects on the GSI/FAIR-Campus will become continuously more important. Work efforts on infrastructure, accelerators and experiments on both the existing GSI and the future FAIR accelerator complex get more and more interlinked. This was especially visible during the discussion of the beam time scheduling for the upcoming five years and its coordination with FAIR installation.

Significant progress was made in the upgrade project for the UNILAC post-stripper. Production of various components is in full swing. One focus was the successful qualification of an additional supplier for the series production of the drift tubes with integrated quadrupoles. In addition a contract was signed with CERN on the copper coating of these drift tubes. At the end of the year also the refurbished "Tankverkupferungshalle" finally reached the status, such that equipment for the Galvanic workshop could be moved in. The facility is now in stepwise commission to finally reach the conditions for the copper coating of the large tanks and cups of the new Alvarez structures. After the coating of a test tank it is foreseen that the work for the tank series starts in late Summer 2024.

The FAIR subproject "FAIR-commissioning" under the leadership of the business area ACC is continuing to take shape and several commissioning workshops on FAIR subsystems took place. This is complemented by taking over the lead of the FAIR internal operation and commissioning cost working group in Summer 2023. Preliminary results were already presented to the FAIR Cost Scrutiny Group, the FAIR AFC and the FAIR Council by the end of the year.

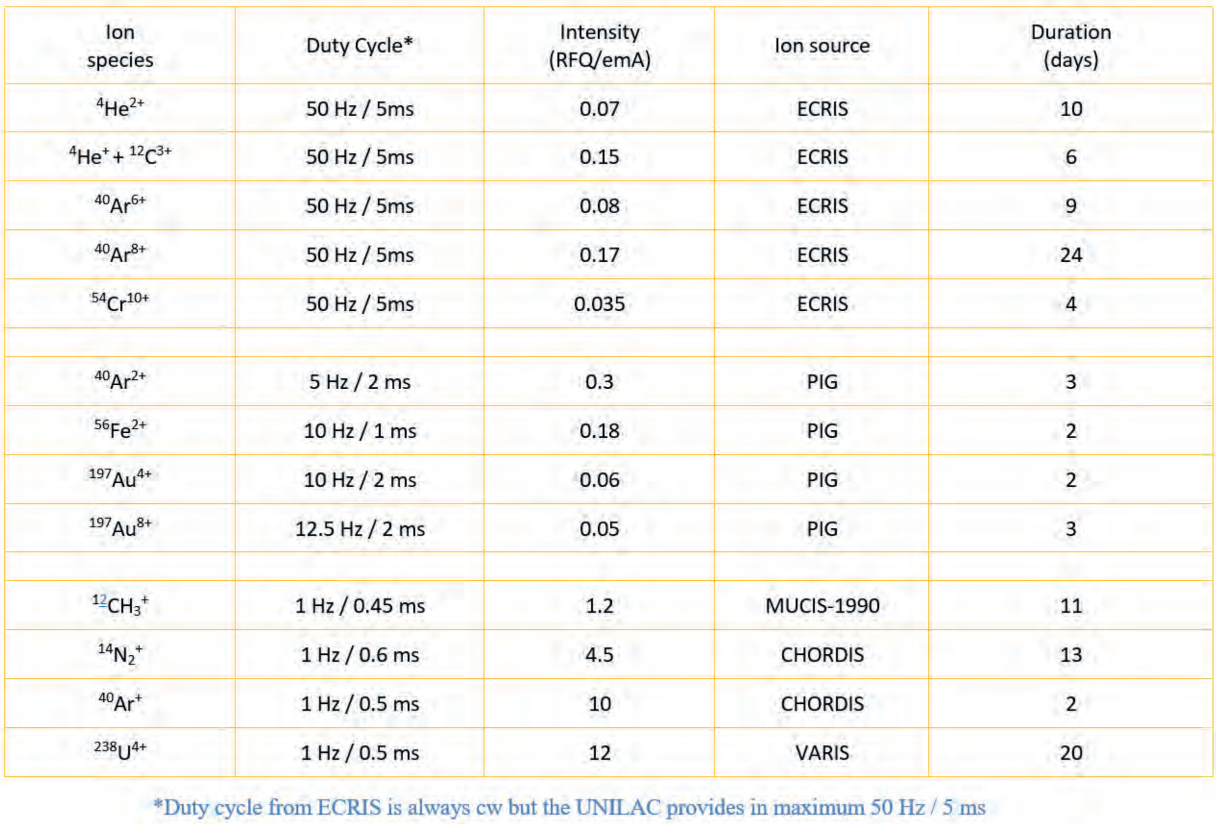
In parallel the Business Area ACC is presently reviewing and optimizing its programs with the universities in the local metropolitan area. Accelerator activities between GSI, Goethe University Frankfurt, Technical University Darmstadt and Johannes Gutenberg University Mainz are discussed with the aim of a further strengthened collaboration in the field of particle accelerators. The links of GSI ACC to those universities but also to national and international partners will be expanded, aimed at supporting education of the next generation of accelerator scientists and at internationalizing parts of the GSI accelerator activities. The involvements in the Helmholtz POF-4 and POF-5 ARD activity and in international projects (focus on EU grants) are being developed with first proposals drafted or submitted.

The operational and scientific activities mentioned above, amongst others, will be described and discussed in detail in the following chapters.

9.2 Ion Source Operation at GSI

Authors: Ralph Hollinger, Aleksey Adonin, Aleksandr Andreev, Rustam Berezov, Michael Galonska, Ralf Lang, Jan Mäder, Fabio Maimone

The ion sources department provided in 2023 various types of ions for an engineering run (see table in Figure 71). 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) in Terminal North, the Penning Ionization Gauge (PIG) ion source in Terminal South and the ECR Ion Source (ECRIS) of the High Charge State Injector (HLI) were supplying the UNILAC in parallel operation. The table below shows the ion species delivered to the accelerator. Representative values of intensities are the analyzed beam currents in front of the High Current Injector HSI-RFQ and of the HLI-RFQ, respectively.



Ion species	Duty Cycle*	Intensity (RFQ/emA)	Ion source	Duration (days)
$^{4}He^{2+}$	50 Hz / 5ms	0.07	ECRIS	10
$^{4}He^{+} + ^{12}C^{3+}$	50 Hz / 5ms	0.15	ECRIS	6
$^{40}Ar^{6+}$	50 Hz / 5ms	0.08	ECRIS	9
$^{40}Ar^{8+}$	50 Hz / 5ms	0.17	ECRIS	24
$^{54}Cr^{10+}$	50 Hz / 5ms	0.035	ECRIS	4
$^{40}Ar^{2+}$	5 Hz / 2 ms	0.3	PIG	3
$^{56}Fe^{2+}$	10 Hz / 1 ms	0.18	PIG	2
$^{197}Au^{4+}$	10 Hz / 2 ms	0.06	PIG	2
$^{197}Au^{8+}$	12.5 Hz / 2 ms	0.05	PIG	3
$^{12}CH_3^{+}$	1 Hz / 0.45 ms	1.2	MUCIS-1990	11
$^{14}N_2^{+}$	1 Hz / 0.6 ms	4.5	CHORDIS	13
$^{40}Ar^{+}$	1 Hz / 0.5 ms	10	CHORDIS	2
$^{238}U^{4+}$	1 Hz / 0.5 ms	12	VARIS	20

*Duty cycle from ECRIS is always cw but the UNILAC provides in maximum 50 Hz / 5 ms

Figure 71. Ion source operation at GSI in 2023.

Operation of high current ion sources (MUCIS-1990, CHORDIS and VARIS) in Terminal North was in general stable, high performance and without any issues. The whole block of 11 days of CH_3^{+} operation was performed with a single source (MUCIS-1990) with only one filament service. The ion beam current in front of the HSI-RFQ was up to 1.2 emA, higher beam currents were not requested. That allowed to achieve 0.65 emA of proton beam and 0.8 emA of C^{6+} beam at the end of the transfer channel (TK), which corresponds to $4 \cdot 10^{11}$ particles and $8.2 \cdot 10^{10}$ particles in a 95 μs pulse for protons and for C^{6+} respectively. The gas consumption for Methan operation was approximately 0.5 liters per day.

By the operation of Ar^{+} beam with CHORDIS a high brilliance operation mode (using a weak focusing strength of the post-acceleration gap) has been demonstrated, allowing to reach high beam transmission through HSI-RFQ (up to 95%) for a high current (9 mA) Ar^{+} ion beam (see Ion Sources R&D report).

The N_2^{+} molecular beam has been provided by the CHORDIS ion source. The whole beamtime block of 13 days has been performed with a single source, no service was necessary. Out of 4.5 mA of N_2^{+} molecular beam in front of the HSI-RFQ it was possible to reach 6.5 emA of N^{7+} ion beam at the end of the transfer channel (TK), that corresponds to $5.5 \cdot 10^{11}$ particles in a 95 μs beam pulse.

The uranium block was the longest in this engineering run, 20 days. High current U^{4+} ion beam was provided with VARIS. Out of 12 emA of U^{4+} beam reached in front of the HSI-RFQ it was achieved 6 emA of U^{28+} and 3 emA of U^{73+} ion beams. That corresponds to particle intensities of $1.3 \cdot 10^{11}$ for U^{28+} and of $2.5 \cdot 10^{10}$ for U^{73+} particles in a 100 μs beam pulse at the end of the UNILAC transfer channel (TK).

The Penning ion source was in operation for the engineering run with Au^{8+} for operator training and with Au^{4+} and Fe^{2+} for commissioning and test of pulsed gas stripper in UNILAC.

The ECRIS at the HLI provided $^{4}He^{2+}$, $^{54}Cr^{10+}$, $^{40}Ar^{6+}$, and $^{40}Ar^{8+}$ beams. For the first time, an operation with a mixed $^{4}He^{+}+^{12}C^{3+}$ beam has been established.

The $^{54}Cr^{10+}$ ion beam has been produced to test the material consumption as well as the beam intensity and stability. The ion beam has been delivered to the X8 beamline to test the beam transmission for the forthcoming physics run requested by the super heavy elements group. The last days of the ion source operation were affected by several high-voltage sparks that limited the ion source performance. The ceramic insulator in the extraction column had to be replaced due to the deposited material. Another test is planned before spring 2024 to verify the source performance. It is expected to achieve comparable intensity and stability to those obtained during the Cr experimental campaign at the test bench.

A mixed carbon-helium ion beam has been provided for simultaneous carbon ion beam therapy and helium radiography. The request in terms of intensity and C-to-He-ratio has been fulfilled by setting up a steady carbon ion beam of approximately 150 eμA ($^{12}C^{3+}$) containing a helium particle fraction of about 10 %, i.e. approx. 5 eμA ($^{4}He^{+}$) in front of the subsequent Linac-Synchrotron accelerator chain. An Optical Emission Spectrometer was fundamental to setting and maintaining the requested C-to-He-ratio for the entire mixed beam block.

$^{40}Ar^{6+}$, $^{40}Ar^{8+}$, and $^{4}He^{2+}$ stable beams have been provided for the commissioning and operation of Cryo-module CM1 of the CW-Linac.

9.3 Engineering run 2023

Authors: Markus Vossberg, Stephan Reimann

A five-months user beam time was planned for the beginning of February 2024 after a 1.5-year break. Due to the large number of activities carried out on the accelerator components and the related infrastructure during the long shutdown since July 1, 2022, it had become necessary to provide for a sufficient commissioning time slot to ensure the operational capability of the entire facility. Besides machine beam time for advanced investigations and further developments to the existing facility were highly demanded. A large number of proposed machine studies were assessed and prioritized by the machine coordinators and the operation management. For this reason, a dedicated engineering run lasting approx. 6 weeks was prepared from November 6 to December 19 (Figure 72).

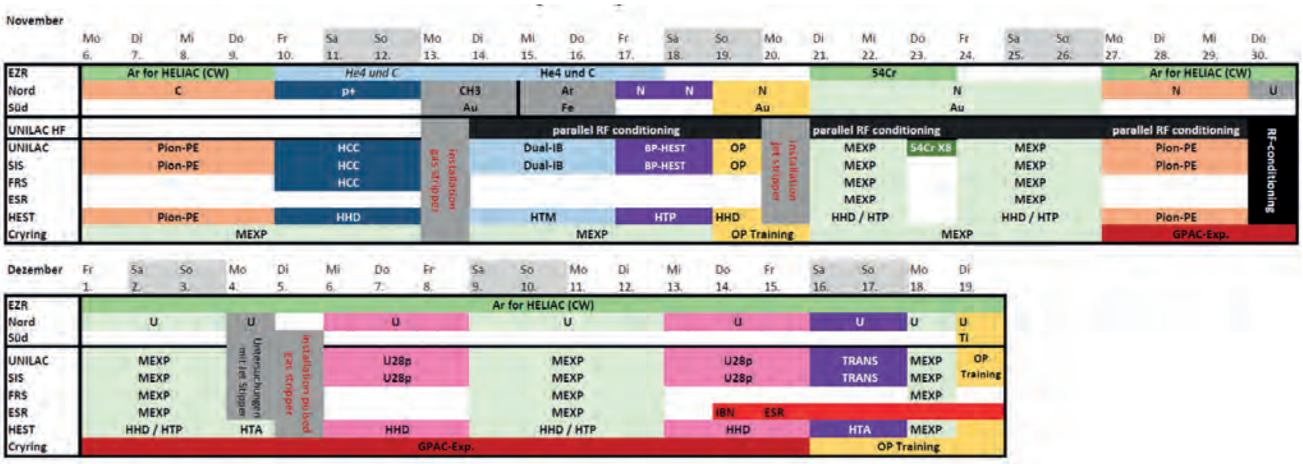


Figure 72. Detailed plan of the engineering run incl. accelerated ion types.

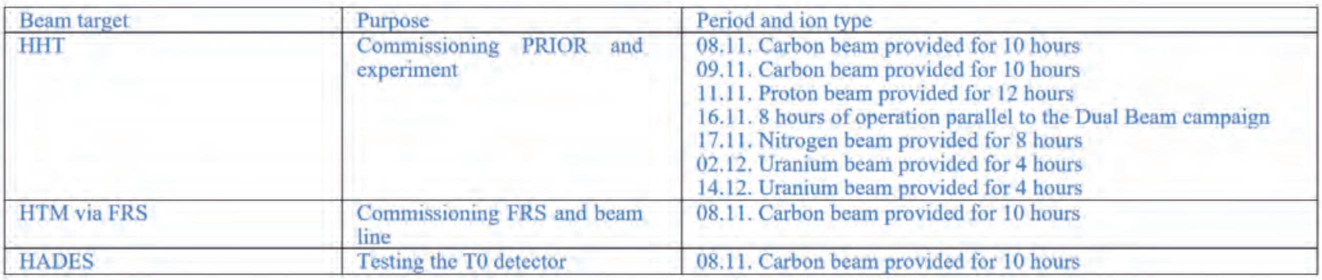
Campaign goals and machine experiments

Main objectives of the engineering run:

- re-commissioning of the entire accelerator chain with beam
- verification of the requested operating modes for standard user operation in 2024
- implementation of seven different campaigns dedicated for the development of new operating modes (incl. two blocks for the development of FAIR booster operation with U^{28+} beam using the newly developed H_2-pulsed gas stripper)
- training of the operating teams
- user beam time at CRYRING (top rated PAC experiments)
- beam commissioning of the cw-LINAC advanced demonstrator cryomodule
- execution of approx. 60 prioritized machine studies

Due to delays in the repair of the ESR electron cooler, the bake-out process could not be started on time and the ESR-commissioning had to be postponed to 2024. Except the ESR-commissioning all goals of the engineering run were achieved.

For example, a new U^{28+}-beam intensity world record was achieved, as well as a record in operation with Carbon-beam from the methane source. In the dual-beam campaign, a worldwide unique operating mode was established for the first time; two particle types could be simultaneously made available for a single experiment. The new superconducting HELIAC CH-cavities were successfully commissioned with Ar- and He-beam for the first time. The beam intensity requirements for the planned HADES beam time 2025 for pion production were fulfilled with nitrogen and carbon-beam, thus the duration of the experiment campaign can now be determined. Around 50 of the planned machine experiments were carried out during the engineering run. For most machine experiments, only one shift was planned. In order to enable the experimentation time. This was only possible thanks to the fast and precise machine settings made by the operators to achieve the desired intensities and beam energies. Another goal was the commissioning of the pulsed gas stripper. The optimal stripper pressure settings were accomplished for several types of ions. Since the pressure can be adjusted individually for different virtual-UNILAC accelerators, there is nothing to be against using the pulsed gas stripper for the future beam time for standard operation. In addition to the very ambitious and packed engineering run plan, every minor time gap was used to supply additional, also unplanned beam tests. The additionally supplied test experiments are shown in the following table in Figure 73.



Beam target	Purpose	Period and ion type
HHT	Commissioning PRIOR and experiment	08.11. Carbon beam provided for 10 hours 09.11. Carbon beam provided for 10 hours 11.11. Proton beam provided for 12 hours 16.11. 8 hours of operation parallel to the Dual Beam campaign 17.11. Nitrogen beam provided for 8 hours 02.12. Uranium beam provided for 4 hours 14.12. Uranium beam provided for 4 hours
HTM via FRS	Commissioning FRS and beam line	08.11. Carbon beam provided for 10 hours
HADES	Testing the T0 detector	08.11. Carbon beam provided for 10 hours

Figure 73. Table of bonus program – unscheduled beam targets supplied.

9.4 UNILAC Machine Investigations

Authors: Winfried Barth (HIM & GSI), Hartmut Vormann, Uwe Scheeler, Markus Vossberg

The UNILAC machine investigation program during shutdown and engineering run was focused on high current proton, carbon, argon and uranium beam operation [1] (including front-to-end UNILAC emittance measurements and dedicated investigations on the multi charge state uranium beam operation).

Investigations with a high current argon beam at the HSI have been conducted in June 2023. With improved RFQ-matching, the upgraded superlens [2] and the pulsed gas stripper with hydrogen gas 28 mA of $^{40}Ar^{11+}$ beam intensity was accomplished at 1.4 MeV/u (corresponding to 430% of UNILAC design limit). Emittance measurements at the HSI-RFQ exit were performed with the mobile emittance device at the position of the dismantled superlens (while the superlens rods replacement and related work took place). As a result it could be shown, that the transversal RFQ-beam emittance has a minimum at the RFQ working point (0.3 mm*mrad, 4*rms, 90%, norm.), whereas for lower and higher RF voltages the emittance is enlarged. With the small emittance at the working point standard operation can be conducted with high efficiency as foreseen, without changes of the operation scheme.

Protons were provided from methane gas CH_4 in the MUCIS ion source, accelerated as singly charged CH_3 in the HSI and stripped to protons and carbon ions in the gas stripper section. Proton acceleration with larger synchronous phase in the Alvarez section (57° instead of 30°) allowed the use of reasonable RF voltages, avoiding a transmitter setup for extremely low RF power. An Alvarez beam intensity of 1.2 mA and 0.75 mA at the end of the transfer channel (TK) resulted in $1*10^{11}$ particles at SIS Flattop. Significantly higher proton beam energies by the use of largely increased RF voltages in Alvarez 4 could not be reached.

High current carbon beam operation, generated by MUCIS (applying methane gas operation), suffered from a reduced stripping efficiency in the jet gas stripper (reduced stripper target density, due to the new explosion safe roots pumping station). A beam intensity of 0.6 mA C^{4+} behind UNILAC resp. 0.7 mA C^{6+} at TK end has been achieved. In order to provide for a sufficient high intensity beam for pion production nitrogen beam with 5.4 mA $^{14}N^{7+}$ could be injected into SIS18.

In 2023, the UNILAC was in operation for 45 days in an engineering run and 25 days in dry-runs. No physics user beamtime took place due to the expected extremely high energy costs. Beam operation ran quite reliably, there were no long-standing breakdowns. Most remarkable interruptions were the ramping misbehavior of the sweeper magnet power supplies of the transfer channel charge separator (solved after replacement of hardware components), and some faults of RF cavities (e. g. Alvarez phase switches, buncher BB6 plunger drive, HLI-IH transmitter tube contact). It should be noted that the pulsed gas stripper was in operation for almost the full engineering run period (provisional operation with nitrogen gas; with hydrogen gas two periods of three days each). Based on the good experiences made, it was decided to use the pulsed gas stripper also in the user beamtime 2024.

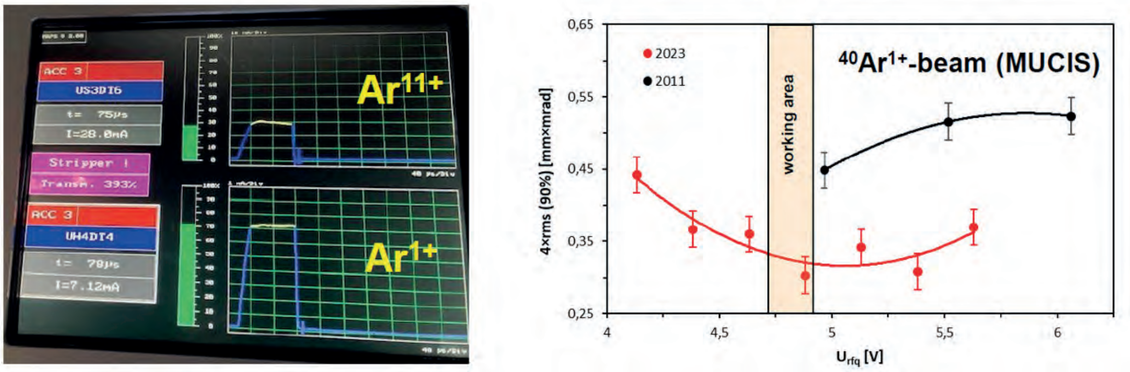


Figure 74. Left: Transmission of the high current argon beam: 28 mA Ar^{11+} behind HSI and gas stripper section (pulsed stripper, hydrogen gas). Right: Transversal $^{40}Ar^{1+}$ HSI-RFQ beam emittance with minimum emittance at the RFQ working point.

- [1] P. Spiller et al., Uranium beam investigations at SIS18, this report.
- [2] U. Scheeler et al., UNILAC shutdown activities 2023, this report

9.5 Progress report on the UNILAC pulsed gas stripper

Authors: Peter Gerhard, Michael Maier

Heavy ion beams are fundamental for the FAIR research programme. The UNILAC high current injector HSI delivers these beams with high intensities, but low charge states. To allow for efficient acceleration in the Alvarez drift tube linac (DTL) and later in the SIS18 synchrotron, a gas stripper is located between the HSI and the Alvarez DTL to reduce the mass-to-charge ratio below 9. The currently used continuously operating nitrogen jet stripper will be replaced by a pulsed gas stripper, allowing to introduce hydrogen instead of nitrogen as stripping target. This will enhance the stripping efficiency for heavy ions, which currently is on the order of 0.14, by up to 60%. This pulsed gas stripper, under development since several years, is currently being transformed from an experimental setup into a system suitable for regular operation.

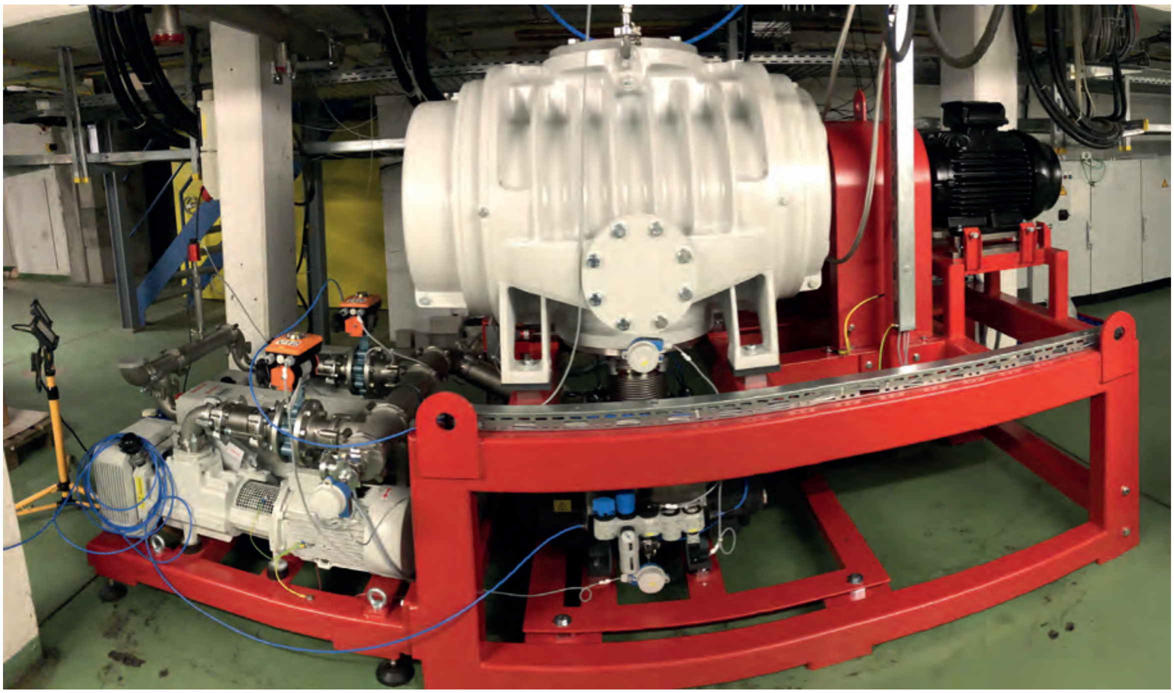


Figure 75. The new, ATEX compliant roots pumping station. It consists of a large roots pump as the first stage on top of a smaller roots pump (not visible) forming the second stage, and finally two large, single stage rotary vane pumps in parallel on the left side as the third stage of the pumping station. All pumps are mounted on a red steel frame.

A major step achieved in 2023 was the installation and commissioning of a new, large roots pumping station. The main feature is its ATEX (ATmosphères EXplosives) compliance, which was found to be necessary for the safe operation with hydrogen as a result of a thorough risk assessment carried out earlier. As a secondary benefit of this replacement, the existing roots pumping station, being more than 40 years old, was modernized. The old pumping station was dismantled in spring 2023, moved 15 m upstream the HSI, and reinstalled. It will continue to serve as a roughing pump for the large UNILAC RF cavities. The new pumping station was delivered to GSI and installed in May. During the exchange, a baffle was found in the 300 mm vacuum pipe connecting the main stripper chamber with the roots pumping station. It was dismounted in order to increase the conductance of the pipe and let the high pumping speed of the new roots pump come into effect. Commissioning lasted until mid-August, concluding with the exchange of the floating ring seal of the main roots pump due to unacceptable high operating temperatures. Final elimination of oil leaks in the cooling loop took until October, and proper cooling of the seal was finally achieved in January 2024. The pumping station was already in full operation during the engineering run end of 2023.

Another milestone was reached with the extension of the central gas alarm system. Four additional gas sensors were installed during the shutdown, providing the safety monitoring necessary for regular operation with hydrogen. The sensors monitor gas leakages in the bottle cabinet, in the gas control cabinet and at the gas stripper in the UNILAC tunnel. In the future, the adequate dilution of hydrogen in the vacuum exhaust will also be monitored. An optical and acoustical alarm was installed in the vicinity of the planned gas stripper facility. The extension was commissioned and went live just before Christmas.

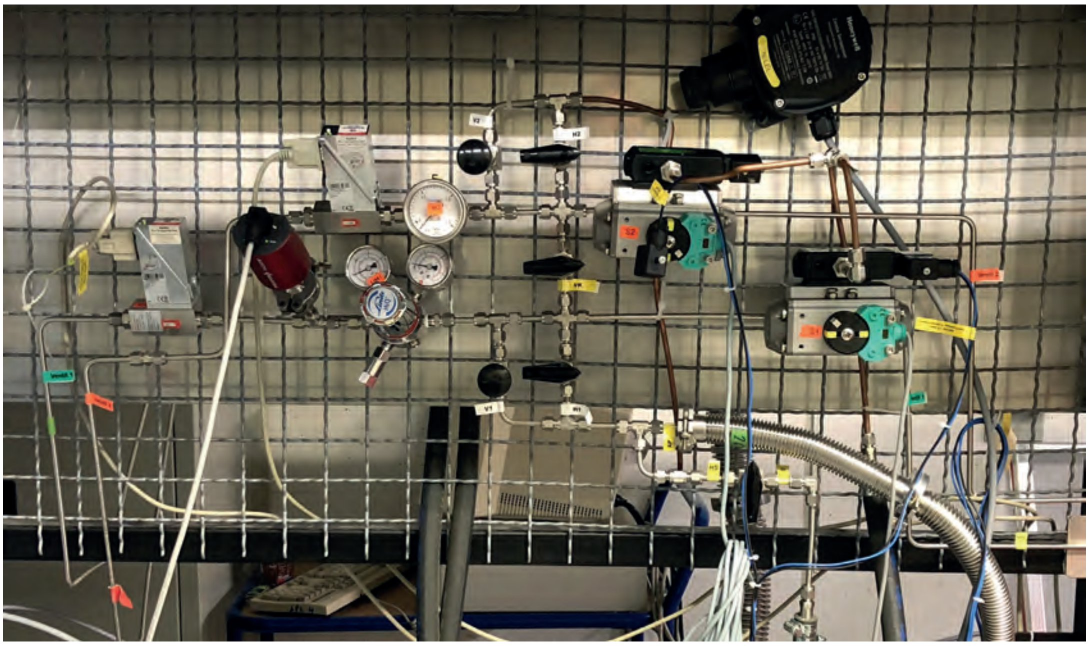


Figure 76. **The preliminary gas control setup of the pulsed gas stripper, as upgraded for the machine experiments during the engineering run in November. The special low-pressure regulator featuring two pressure gauges is visible in the left centre of the photo.**

During the year, the focus of the project shifted to the procurement of the remaining major constituents of the planned pulsed gas stripper facility, beginning with the gas control station. In contribution to this, machine experiments were conducted in November. The goal was to perform a survey of the stripping properties for as many different elements as possible, ranging from light through medium up to heavy ions, scanning the full range of target densities available with the current setup for both nitrogen and hydrogen. This data is needed as a basis for specifying the gas pressure and flow ranges to be provided by the gas control station in order to cover all operational requirements. During four shifts, allotted on four consecutive days to allow for the necessary ion source exchanges and beam setups, a total of 81 charge state spectra were measured for the elements C, Ar, Fe, Au and U. In preparation for these measurements, the preliminary gas control setup was upgraded with a special low-pressure regulator to extend the pressure range below atmospheric and hence the target densities available.

During operation in November, an unexpected low performance of the jet stripper was observed especially for very heavy ions like uranium. A thorough investigation and comparison with the pulsed stripper revealed the stripping efficiency to be reduced by about 10%. The removal of the baffle in the course of the exchange of the pumping station mentioned above is suspected to be the (so far unconfirmed) cause for the degradation of the jet stripper performance. Since the pulsed stripper was not affected, it was consequently proposed to employ it for the user beam time in 2024, notwithstanding its preliminary status. Operation would be restricted to using nitrogen as stripper gas to avoid the so far not completely resolved safety issues associated with the use of hydrogen for regular operation. Operating scenarios, boundary conditions, related costs, manpower requirements including on-call duty, and necessary preparations as well as the impact on the overall project progress were compiled, and first preparatory steps already (partly) executed until end of 2023.

9.6 Ultimate Heavy Ion Beams Intensities in UNILAC and SIS18 for FAIR

Authors: Winfried Barth (HIM & GSI), Lars Bozyk, Peter Spiller

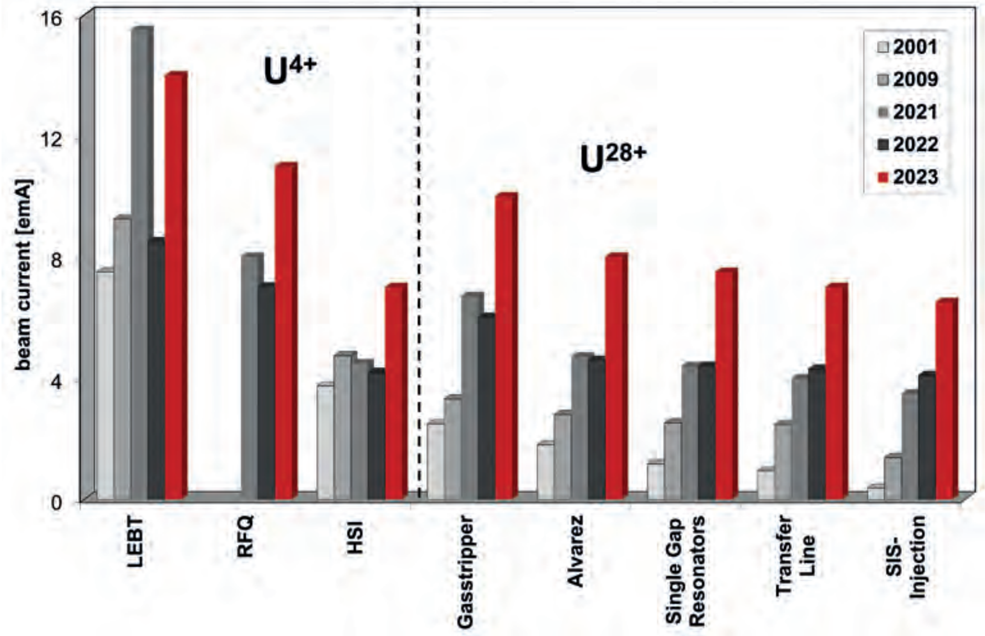


Figure 77. History of number of U^{28+}-ions in UNILAC during acceleration and transport to SIS18

New intensity records have been achieved with heavy ion beams in the UNILAC and SIS18 accelerators. In the frame of a machine development campaign end of 2023, up to 7 emA of U^{28+} pulsed heavy ion beam has been generated and provided for injection into SIS18 (see Figure 77). This increase was possible by means of the high-pressure Hydrogen stripper in the UNILAC, an upgrade of the superlens matching the beam between the RFQ and the IH section and careful setup of VARIS ion source and low energy beam transport to the HSI-RFQ. There is no other linear accelerator worldwide providing heavy ion beams with such an intensity.

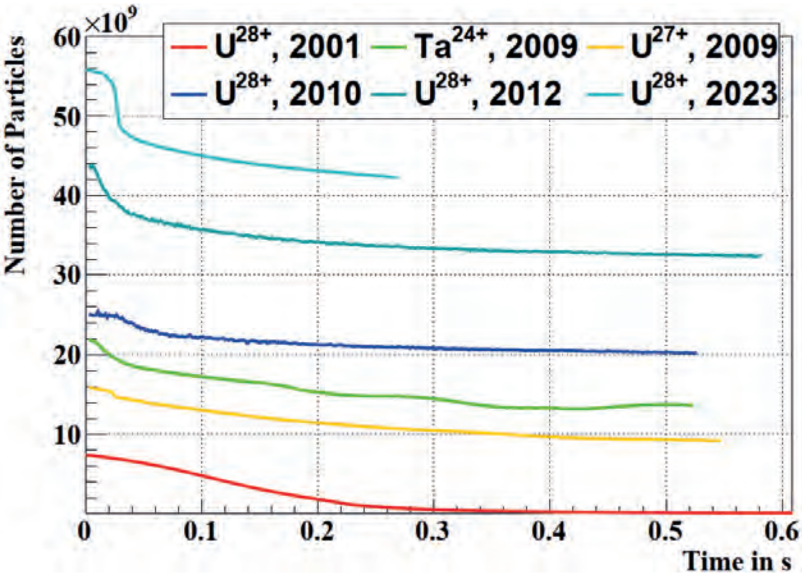


Figure 78. History of the number of U^{28+}-ions as a function of time during the acceleration cycle in SIS18. All recorded data show acceleration cycles. Different lengths are due to different ramprates. Large losses at the beginning are caused by the rf capture process and ramp start, further losses due to ionization processes. Ta^{24+} has very similar cross sections to U^{28+}.

With this high intensity beam, a new intensity record for stored and accelerated heavy ions has been achieved in SIS18. The old record intensity for heavy ions accelerated in a synchrotron of the year 2012 was exceeded (Figure 78).

Measurements of the extracted number of ions versus the ramp rate of the magnetic cycle show the expected dependency that faster acceleration reduces ionization loss. It delivers the first experimental proof for the successful major investment into the SIS18 upgrade (Figure 79). The saturation towards higher ramp rates is due to the intensity limit of the UNILAC beam provided for injection.

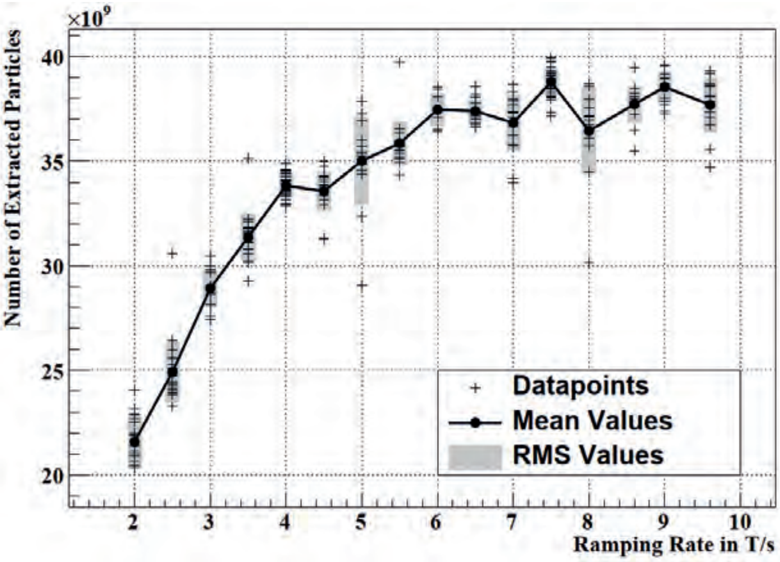


Figure 79. Extracted number of ions as a function of the ramp rate of the main magnets in SIS18

GSI has developed a unique expertise in understanding and simulating charge exchange losses of low charge state heavy ions and dynamic vacuum effects driven by desorption processes. Based on these capabilities, one main postulation made was that for the survival of low charge heavy ions, beside other key parameters, the machine cycle plays an important role. Since the cross sections for charge exchange processes decrease with increasing beam energy, immediate start of acceleration without plateau after injection and as fast as possible acceleration with maximum ramp rate, was always supposed to be the best cycle, enabling the maximum beam survival of low charge state heavy ions. The latest measurements are for the first time, experimental evidence for this underlying assumption and suggests that the major investment into the main power converter upgrade and the development and installation of three new MA cavities for fast ramping has been an excellent approach for increasing the intensity.

Further technical approaches for stabilizing the dynamic vacuum and minimizing charge exchange loss in SIS18 are under development. Cryogenic inserts may deliver extreme pumping power and can be installed at positions with high systematic beam loss or as distributed pumps as inserts in magnet chambers. Both options are presently investigated as prototypes and laboratory set-ups.

Selected publications

- [1] P. J. Spiller, L. H. J. Bozyk, and P. Puppel, “SIS18 – Intensity Record with Intermediate Charge State Heavy Ions”, in Proc. IPAC'11, San Sebastian, Spain, Sep. 2011, paper WEPS003, pp. 2484-2486
- [2] L. H. J. Bozyk, S. Aumüller, and P. J. Spiller, “Investigations on Cryopanels in the Room Temperature Heavy Ion Synchrotron SIS18”, in Proc. IPAC'19, Melbourne, Australia, May 2019, pp. 1372-1374. DOI:10.18429/JACoW-IPAC2019-TUPMP054
- [3] W. Barth, et al., High Brilliance Beam Investigations at UNILAC, Phys. Rev. Acc. Beams 25, 040101 2022. DOI:10.1103/PhysRevAccelBeams.25.040101

9.7 The long shutdown - Overview of 16 months of maintenance work on the GSI accelerator facility

Authors: Miriam Klich, Max Müller, Stephan Reimann

The long shutdown started on July 1st, 2022 and was characterized by three major activities: the renewal of the medium voltage (MV) switchgear called “=AA”, the renovation, installation and commissioning of the ventilation system number 16 (LA16) in combination with the renovation of the roof of the supply rooms and the complex repair of the electron cooler of the experimental storage ring (ESR). The first few months of the shutdown period were summarized in the GSI-FAIR Scientific Report of 2022. The present report will give an overview until the end of the shutdown in October 2023.

Infrastructure and Civil Construction

In mid-January, the last stage of the renewal of the MV switchgear “=AA” was successfully completed, and in mid-February, the commissioning of the LA16 began as planned. Both activities were completed on schedule.

During this shutdown, the fire protection upgrade of the BR2 Radio Frequency (RF) gallery, the reinforcement of the eastern kicker wall in the SIS18 tunnel, and the reconstruction of the radiation protection door between the NE5 and NE6 radiation protection areas were completed.

At the connection point between FAIR and GSI, several FAIR activities were carried out by FAIR on GSI ground, e.g. installation of technical building infrastructure and measuring instruments. Additionally, a wall for radiation protection was built on FAIR site to create the conditions for beam operation on the GSI site while continuing the installations on FAIR site.

The operating system for the machine control system computers has been changed from ACC7 to ACC9 on most devices due to problems with ACC8, and ACC7 is now only accessible to a few users. The main control room was equipped with new monitors in the UNILAC area, and regular maintenance, updates and upgrades were carried out.

From May to June, there was a major survey and alignment campaign that included an evaluation and adjustment. The external §88 test (an administrative procedure to maintain the operational safety from the point of radiation safety) had to be postponed until October due to problems with the internal tests that took place in September.

Machine Activities

UNILAC

An important task at the UNILAC were the installation, testing and commissioning of the superlens with the new rods. During this activity there were problems with the vacuum and new plungers had to be manufactured. The first tests with beam took place in July.

The transfer channel sweeper was modernized and a new user interface of the “Tür Verriegelungssystem” (TVS), the electronic door lock system, was tested in July.

Throughout the entire shutdown, there were a few water and vacuum leaks in the old cavities that needed to be repaired, as well as several beam diagnostic elements.

Regular maintenance of the RF system began in February, following the completion of activities for LA16 in the RF gallery. The commissioning of the RF systems began in May, with the first phase of testing taking place in July.

The reconstruction of the roots pump station for the pulsed gas stripper was carried out from March to June.

The tests of the new emergency stop system at the UNILAC required a partial interruption of the entire UNILAC power supply, but after intensive planning the tests went off without a hitch.

SIS18

The maintenance of the ionization profile monitor (IPM) was able to start at the beginning of 2023, and the main part of the repair of the electrostatic septum took place from February to April.

After successful RF testing of the micro-spill cavity, installation began at the end of June.

The installation of the cryo-insert had to be cancelled in July due to a lack of personnel.

ESR

There were coordination difficulties in ordering the heating shirts, which delayed the work in the ESR and postponed it to the summer holidays, this led to a shortage of staff on other work and caused them to be delayed.

The main activities in the southern part of the ESR, the repair of the dipole and the stochastic cooling, were finished in October, so that the heating could be done in December. The northern part of the ESR was ventilated in May for vacuum and beam diagnostic activities, and the heating was completed in late October.

After a company was found to dispose of the asbestos, the dismantling of the electron cooler was able to continue at the end of February. The heating shirts were delivered in September and the assembly began at the end of September. The assembly could not be completed by the end of the year. Heating is scheduled for January 2024, followed by remaining assembly and commissioning, with the goal of bringing the beam to HITRAP in mid-February.

CRYRING@ESR

From the beginning of 2023 until the summer, a new ion source was installed and tested at CRYRING@ESR.

The repair of the CRYRING@ESR cooler was also affected by the problems with the procurement of the heating shirts and the resulting staff shortage, so that the reassembly started only in August and the heating in October, but still just in time for the engineering run.

HITRAP and HELIAC

The HITRAP beam line has been prepared for the 2024 beam time and the control system has been upgraded with the HITRAP components. The first cryo module for the HELIAC has been installed and tested.

Outlook for 2024

In 2024 there will be approximately 6 months of regular shutdown after the beam time ends in June and a short maintenance break of 2 weeks in April. The long period will contain dry-runs, device test blocks and time for UNILAC RF commissioning. The shutdown will be used to start on the reconstruction of the experimental hall housing all the low energy (UNILAC type) experiments. Other shutdown works are being planned in the moment but will be limited by resources that are also needed for installation and assembly of accelerator components on the FAIR site.

9.8 UNILAC Shutdown activities 2023

Authors: Uwe Scheeler, Hartmut Vormann, Winfried Barth (HIM & GSI), Markus Vossberg

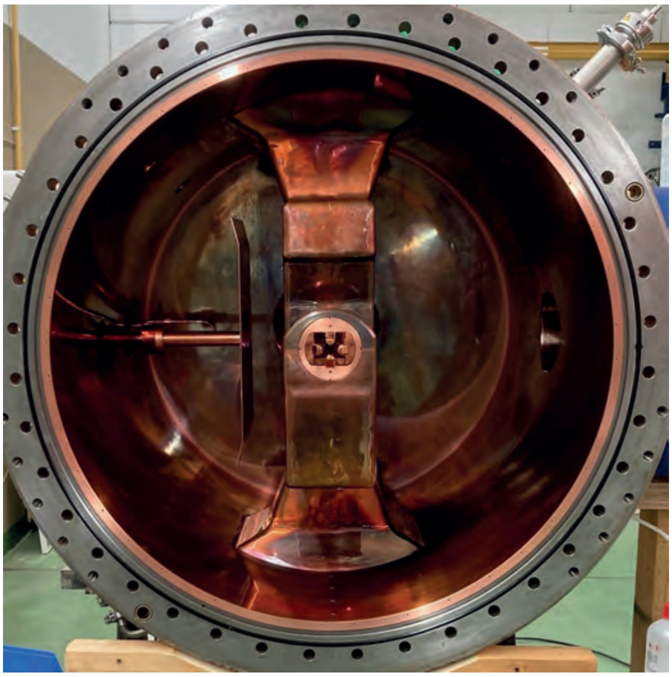


Figure 80. View into HSI-superlens with a new plunger (left side).

In 2023 the shutdown measures, which had been started the previous year, have been continued. The installation of the new rods of superlens took place in January. After the exchange, the resonance frequency increased by about 170kHz. With the original plunger configuration, the nominal operation frequency of 36.136 MHz could not be reached. The design of the plunger was adapted by increasing the capacity of the structure (increased surface area and reduced distance to the rods). In parallel, the entrance aperture has been reduced to 12mm in order to prevent beam loss on the rods, which led to unstable beam operation in the past. A beam measurement campaign provided for emittance characterization in front of the cavity. The beam transport has been adapted to match the superlens conditions. The superlens RF commissioning results in improved operation performance, less power is needed to provide for the same acceleration field; the breakdowns due to beam loss have been reduced substantially.

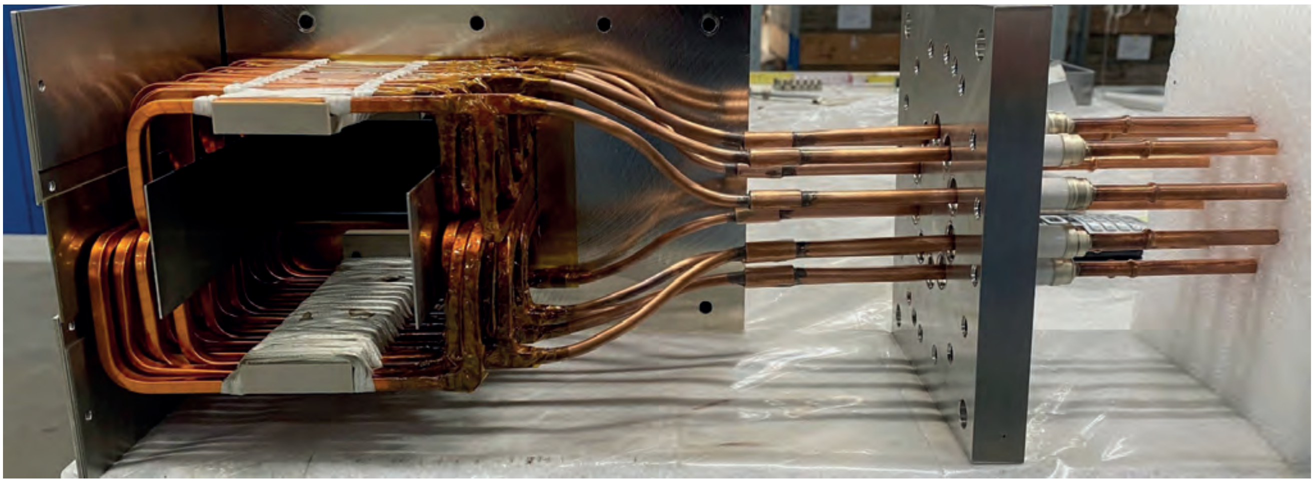


Figure 81. Septum magnet with new coil and cooling water connections (right).

Another activity was the fabrication and exchange of the magnet coils of the septum magnets in front of the experimental hall. The coils are installed in vacuum; their out-gassing rate has to meet a certain limit. Altogether three new coil pairs have been fabricated. Due to the fact that the corresponding three yokes vary in their dimensions more than it was tolerable. The fabrication and installation for each coil had to be performed separately and adapted to the tight available space (see Figure 81). Another challenge was the certification of the feed-throughs of the cooling pipes concerning operation current (600A) and temperature (55°C). Cooling tests have been conducted in order to provide for reliable operation. In case of interruption of the water flow, two interlock systems that survey the water flow and the resistance of the single cooling circuits of the coils resulted in a switch off of the power supply.

The cabling and configuration of the new vacuum control system was finished in August; commissioning took place before the engineering run started in November. Now all components of UNILAC and the transfer line except the experimental hall are controlled by the newly installed system. Data logging allows the survey, while one can monitor the trends of the pressure values in order to organize preventive maintenance.

The upgrade of the emergency switch-off system and the exchange of the medium voltage switch gear have been finished as well. Several unexpected as well as planned power breakdowns led to a switch off of the complete internal power grid. A lot of preparation effort in particular for cooling circuits and vacuum systems was necessary. The complete vacuum system was stressed due to these breakdowns and switch-offs. At Alvarez 2A, the coupling loop got a leakage. The loop has been replaced by the last spare part. Unfortunately, the repair measures for the other aged and defective coupling loops were up to now not fully successful.

After the tendering process, the fabrication of the new drift tube UN5QT4 at the High Charge State Injector started and is still ongoing. The new magnet design is finalized, but the design of the drift tube shell is still under discussion. The construction and manufacturing of two technically demanding bellows needed for the vacuum connection of the pedestal are not yet fixed.

At the High Charge State injector beam transport line, a long-lasting repair of the damaged Bunch Structure Monitor was successfully finished in August, the monitor was installed and recommissioned in September and allowed proper measurements for the HELIAC Advanced Demonstrator beam commissioning.

9.9 ESR shutdown activities

Authors: Markus Steck, Regina Heß, Roland Joseph, Sergey Litvinov, Bernd Lorentz, Claudius Peschke, Ulrich Popp, Jon Roßbach, Ina Schurig

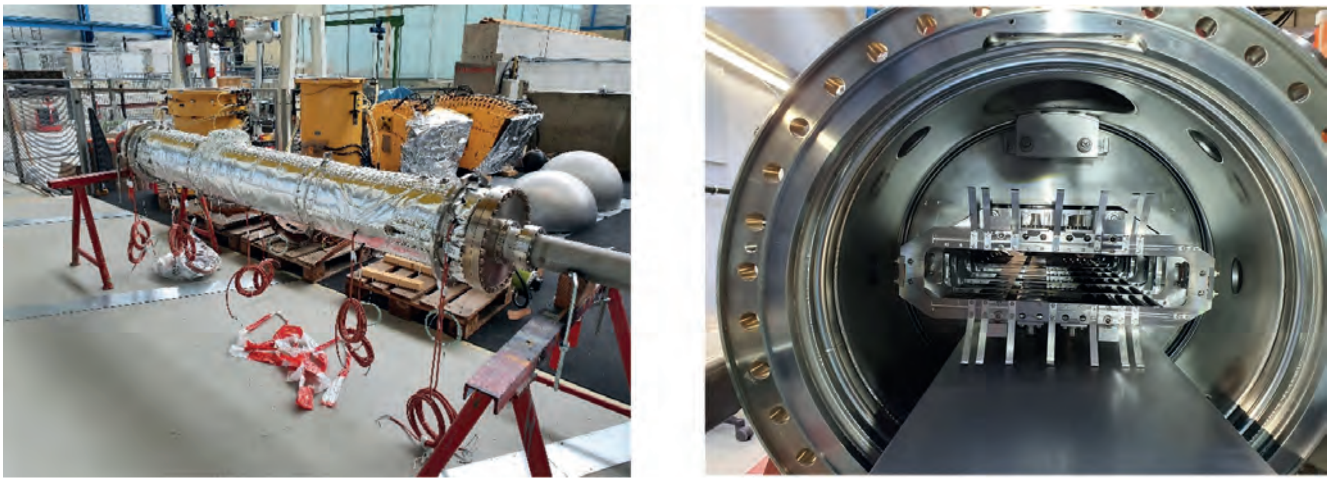


Figure 82. Vacuum tube of the electron cooling section after repair and installation of new bake out jackets (left), and installation of the repaired stochastic cooling kicker array inside the vacuum chamber of the quadrupole magnet (right).

The long ESR shutdown started in July 2022. The full year 2023 was needed to complete all planned activities. Just in time for the 2024 user run the ESR was ready for beam operation.

The major activity, which finally ruled the total duration of the shutdown, was the repair of the electron cooler. The electron cooler had to be disassembled completely in order to fix a short to ground of the central drift tube. The complete disassembly was necessary to have access to the components of the drift tube in the inner part of the cooling section. The reason of the short to ground was found after disassembly, the short was due to a broken high voltage cable which was replaced. The long duration of the intervention was caused by the finding of asbestos containing thermal insulation material and the need to replace all bake out jackets as the installed material was not in accordance with present safety rules. For the disassembly and the disposal of the asbestos containing material a certified company had to be identified and mandated after receiving the special permit by authorities. The exchange of bake out jackets was impeded by the lack of documentation of the existing jackets. As a consequence, the old jackets had to be mapped after disassembly for the order of new jackets. This resulted in another waiting time for the manufacture of the new jackets before the assembly of the electron cooler could start. During the cooler assembly the gate valves at both ends of the cooling section were replaced by new ones, as the old ones had shown first indications of wear and undependable operation. The mechanical disassembly and service work at the electron cooler suffered from the fact, that the documentation of the mechanical set-up is very inadequate to prepare any intervention and can be a problem for future services.

Over the years various electrodes of the stochastic cooling system showed bad electrical contacts which resulted in reduced cooling efficiency. To study the mechanical aspects of the electrode system the kicker electrodes located in the quadrupole magnet were inspected. This required the disassembly of the yokes and coils of a quadrupole and a sextupole magnet in order to have access to the vacuum chamber which houses the kicker electrodes. After disassembly disagreement between existing drawings and the actual set-up were found. For future interventions or modernization of the system the documentation of the set-up was updated. After disassembly the whole system was reworked mechanically and various modifications were implemented. The final assembly was successful and after bake out of the vacuum section the kicker electrodes showed good electrical contact. It is expected that the complete kicker system will be available for efficient cooling.

Some conductors of the pole face windings of one dipole magnet which are powered to flatten the radial field distribution had developed leaks of the water cooling pipe. The leaks had required a stop of the powering of the respective circuits for lack of water cooling. Replacement of the pole face windings required the dismantling of the dipole vacuum chamber to have access to the coils. The replacement by a spare coil system required cutting the old coils and soldering of the spare coils to the terminals in situ. Finally, the vacuum chamber was installed and the vacuum section was baked out. The successful repair allows to operate the pole face winding system in the optimum way to provide large momentum acceptance of the ESR.

The sputter ion pumps in both arc sections of the ring were replaced by new ones. The pumping speed of the old pumps had decreased. In the target and the cooler section NEG-pump modules were installed in addition to the titanium sublimation units in order to increase the pumping speed for hydrogen. The achieved vacuum pressure after bake out in the low 10^{-11} mbar range in all ESR vacuum section promises improved beam lifetime for the scheduled operation of the ESR with low energy beams.

9.10 CRYRING@ESR Operation, Engineering Run and Machine Experiments

Authors: Frank Herfurth, Zoran Andelkovic, Svetlana Fedotova, Claude Krantz

The low energy storage ring CRYRING@ESR has gone through an extensive shutdown starting mid 2022 until end of October 2023. The shutdown concluded with machine experiments within the engineering run. During the last weeks of 2023 CRYRING@ESR was in operation for two FAIR Phase-0 physics experiments using the local injector. About 50 shifts have been supplied with Mg^+ and Ne^{3+} beams about 10 times more intense than possible in previous years.

The long shutdown was used to repair and upgrade bake out and other vacuum equipment at the electron cooler. For this the electron cooler was completely dismantled, most heating jackets were replaced and some chambers were internally coated with non-evaporable getter material. Additionally, the main pumping stations for electron gun and collector, previously based on cryogenic pumps, were renewed and equipped with modern ion getter pumps. A set of drift tubes was added to the merging region between electrons and ions as a way to vary the electron energy locally while maintaining a fixed electron cooler terminal voltage. Finally, a set of so called “clearing electrodes” was installed just before the collector to remove unwanted ionization products from the electron beam.

The local ECR ion source was also refurbished. After the old permanent magnet setup failed last year, a new permanent magnet assembly was purchased. The old ionization chamber was leaking ever so slightly water into the ionization volume preventing the efficient production of higher charge states. A new chamber was produced in-house using a hopefully more robust stainless-steel body. First tests showed that the material change from copper to stainless steel did not deteriorate the ion source performance. Besides the standard ions (D^+, Mg^+, Ne^{3+}), some elements have been tested for the first time in this source to prepare for later experiments. It turned out that it is not possible to produce enough intensity for injection into CRYRING@ESR for W^{7+} or even higher charge states. However, it was demonstrated that this 10 GHz ECR source can be used to produce S^{3+} ions in sufficient quantities (about 1eμA) from Bi_2S_3.

In 2023, the development of an ionization profile monitor that can be used even for the softest beams was finished and a first version has been built. The detection principle of an IPM is based on ion beam created ionization of residual gas atoms. The ionized residual gas atoms are then accelerated in an electric field across the stored ion beam onto a spatially resolving detector. This electric field disturbs the ion beam stored in the ring, especially at low rigidity. Hence the new Low Energy IPM has a set of compensation electrodes added, which were shaped by careful simulations. A first test using an ion beam at the local injector showed that despite their small size they do compensate for the distortions by the main field of the detector. The new IPM is ready to be installed into the ring during the upcoming shutdown.

In order to improve the efficiency of the multi-turn injection system the long shutdown was used to analyze the present system in detail. Simulations yielded the proper expected positions of the electrodes and 3D measurements of the real-world components allowed for a proper comparison. It turns out that the previously used electrode positions were calculated without certain restrictions of the beam pipe and hence did not yield the best possible position. Based on this the engineering run was used to measure several positions and a new optimal position has been determined. This finally led to a much-improved intensity especially for very soft beams like Ne^{3+} with more than 1.5·107 Ne^{3+} ions accelerated and cooled. Figure 83 summarizes the optimization process for Ne^{3+} beam. First, several positions of the electrostatic septum have been tested with short ion bunches. The ion bunch was chosen to be shorter than it takes to travel one turn. Second the bunch length was increased and injected during the time it takes for several turns accumulating ions during the process.

2024 will be governed by the on-line period in the first half of the year where CRYRING@ESR will supply different beams to different experiments ranging from O^{2+} to Au^{75+}. Technically, the shutdown in the second half of the year will be used to install the low-energy IPM into the ring and produce a second one along with preparing a 14.5 GHz source that shall be able produce sufficient amounts of W^{17+} ions.

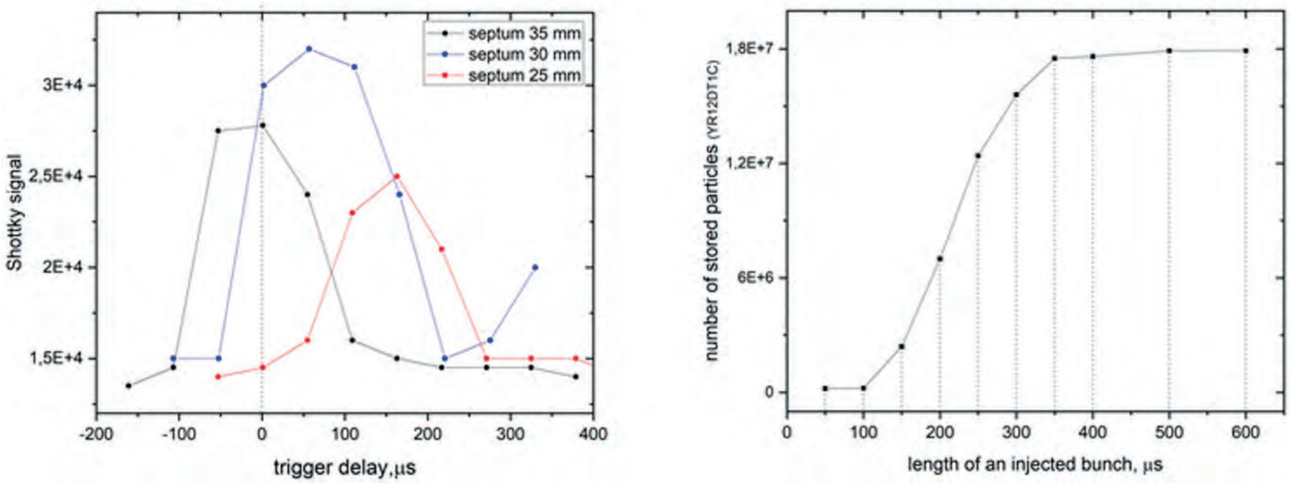


Figure 83. **Optimization of multi-turn injection into CRYRING@ESR. On the left-hand side, the stored beam intensity measured from the Schottky detector signal in relative units is plotted versus the start of the ramping down of the voltage on the multi-turn bump (trigger delay) for three separate positions of the electrostatic injection septum. On the right-hand side, the stored beam intensity is plotted versus the length of the injected ion bunch for the optimum septum position. The vertical lines are mostly 50 μs apart from each other, which is about the time the ions take for one turn.**

9.11 HEST Beam Diagnostics Upgrade

Authors: Christoph Hessler, Plamen Boutachkov, Oksana Geithner, Andreas Reiter, Beata Walasek-Höhne

Beam operation from the SIS18 to the experiments requires a frequent and precise set-up and tuning of the beam in the high-energy beam transfer lines (HEST). To accomplish this task efficiently, the beam lines must be equipped with various types and a sufficient number of modern and reliable beam diagnostic elements. Furthermore, the upcoming move of the main control room to the new FAIR Control Center (FCC) in 2026 requires the digitization of all analog beam instrumentation devices, since no analog cable link to the machine will be installed [1]. Therefore, several beam diagnostic upgrades have been carried out or started in recent years, in order to increase the performance and reliability of the machine and to replace old analog with state-of-the-art digital equipment.

Beam loss monitors (BLM)

Beam loss monitors allow locating and measuring the intensity of beam losses along the transfer lines. This is important to identify bottlenecks and to increase the transmission of the beam to the experiment. Following the successful operation of the BLMs in the HADES beam line for several years, further HEST beam lines to the caves C, D, A, and HTP have been equipped with BLMs during the 2022/23 shutdown. The new BLMs have been used for the first time for the beam set-up and optimization to cave A during the engineering run 2023 and resulted in better beam line settings, which will be used in future physics beamtimes.

Beam position monitors (BPM)

BPMs are used to measure non-destructively the beam position. In HEST, BPMs are installed in the SIS18-ESR beamline, however, the old analog read-out electronics have been absent for many years. In order to put the BPMs back in service, they have been re-cabled during shutdown 2022/23 and they will be operated with FAIR-type DAQ modules. The BPMs are planned to be commissioned during 2024 and should be available during beamtime 2025. With these BPMs it will be possible to develop new advanced steering applications and to test the FAIR DAQ electronics under real operating conditions.

Luminescent screen stations

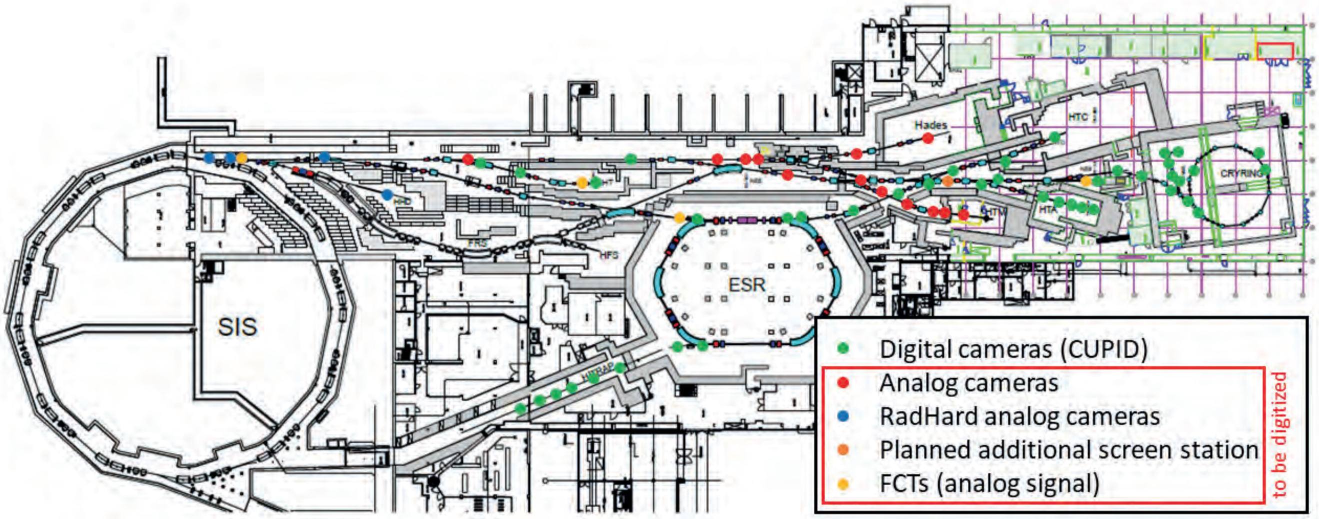


Figure 84. Plan of HEST with the positions of the luminescent screen stations with digital, analog, and radiation hard analog cameras indicated in different colors as of the beginning of 2023. The positions of the FTCs are also shown.

Luminescent screens are essential for measuring the beam position and the beam size during beam set-up. While efforts had been made to upgrade some of the luminescent screen stations in HEST with digital cameras (e.g. to CRYRING@ESR, HHT, and HTA), a large number are still equipped with analog cameras (see Figure 84). For the planned relocation of the control room to the FCC, the upgrade of the remaining stations with digital cameras is mandatory. Therefore, an upgrade project has been launched in 2023, which should last 3 years. In total 13 analog cameras must be upgraded to digital cameras and integrated into the CUPID system (Control Unit for Profile and Image Data). At four locations, radiation hard cameras are required, which are analog. Within the frame of this project, their signals will be digitized and integrated as well into the CUPID system. Furthermore, an additional screen station is planned to be installed in a beam line section, which is currently insufficiently equipped with diagnostics. The upgrade includes also an adaptation of the mechanics (pneumatic drives). Additionally, the diagnostic vacuum chambers will be fitted with fiducials for precise adjustment of the screen position. Hence, an increase in the precision of the measured beam position values is expected.

It is planned to upgrade approximately six screen stations per year. In 2023, two screens towards HADES have been upgraded, as well as screens in the TH2 and TH4 sections and signals of radiation hard cameras have been digitized. For 2024, the upgrade of the remaining cameras in the NE5 area and in the HHD beam line is planned. The cameras in the NE8 area are foreseen to be upgraded in 2025.

Fast current transformers (FCT)

For measuring the beam current of fast extracted beams, 4 fast current transformers are installed in HEST (see Figure 84), which have analog output signals. These signals must be digitized in order to be able to use the FCTs from the FCC. The upgrade work has started in 2023. An intermediate signal digitization solution has been set up for the two FCTs in the ESR beam line for DAQ development. This solution ensures that for the time being the analog signals can still be used in the main control room. The development will continue in 2024.

Particle detector combination (PDC)

Particle detector combinations are setups of three different detectors used for beam intensity measurements: Each PDC consists of a secondary electron emission detector (SEM) for high-intensity measurements, an ionization chamber (IC) for intermediate beam intensities, and a scintillator (SCI) for low beam intensity measurements. New photo-multiplier active voltage divider combinations were installed for scintillator detectors. The dynamic range of the scintillator detectors was increased, allowing intensity measurements from protons to uranium beams. Before the upgrade, intensity measurements of beams lighter than carbon were challenging. In order to detect protons, a special installation with a thicker scintillator detector had to be used, which however was only available for experiments at HTC. With the upgrade one can measure proton to uranium beam intensities using the standard 1 mm thin scintillators installed in TE1, HHD, HAD, and TH4 beam line sections, allowing transmission optimization and calibration of PDCs with lighter beams delivered to all HEST experimental setups.

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9.12 Experimental investigations of the third-order coupled resonance in storage rings

Authors: Giulliano Franchetti, H. Bartosik (CERN), F. Schmidt (CERN)

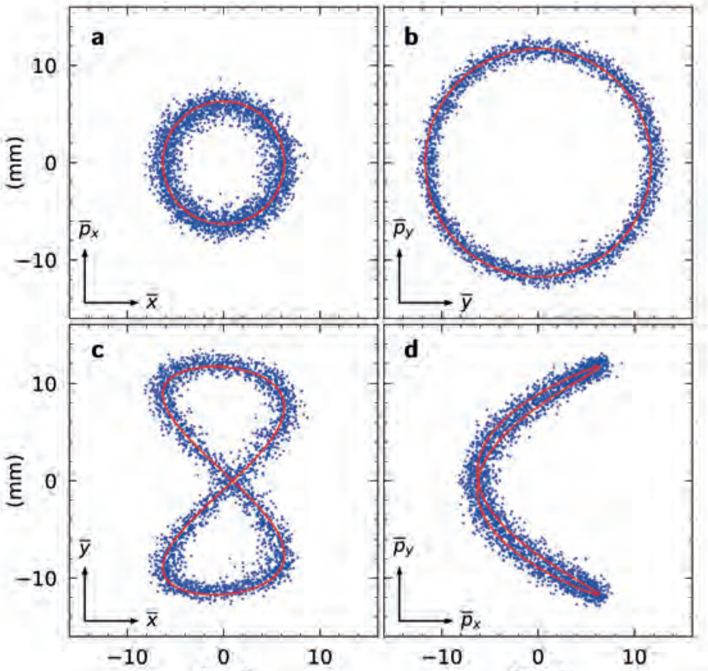

Figure 85. Scaled normalized coordinates (see Ref. [3] for details). Note that in (x, p_x) and (y, p_y) the orbits are circles. Only in the mixed coordinates (x, y) and (p_x, p_y) the effect of the resonance is visible. Note the clear asymmetry of the spatial shape of the orbits: this is an intrinsic property of the resonance. The red curve is the best fit for the experimental orbits to the theoretical fixed-line shape.

The effect of nonlinear resonances is important for the storage of beams as often, beam loss or degradation is the result of the interaction of particle beams on a resonance. The situation is highlighted when varying amplitude detuning brings particles to cross resonances periodically. This may happen in bunched beams due to space charge and/or chromaticity. The resonance crossing may also happen because of beam manipulation during operation, or because of beam acceleration/deceleration. During the deceleration, space charge strength increases, and possible tune migration may induce a crossing of an error resonance. The effect of resonances is understood in terms of excitation (stop-band and strength) and sometimes they are used for operation purposes, such as for the slow extraction or the multiturn extraction. The beam dynamics for coupled resonances is very difficult: even the simpler coupled resonance, the linear coupling, produced by skew quadrupoles is not at all intuitive. The next, simpler, nonlinear resonance is the third-order coupled resonance $Q_x + 2Q_y = N$. This resonance produces a coupling of motion in the 4D phase space, which is very difficult to visualize and parameterize for predicting the beam particle behavior. Despite this, measurements carried out in 2012 at the CERN PS synchrotron gave experimental indications that coupled resonances produced asymmetric halos for high-intensity bunched beams [1]. A perturbative theoretical model [2] may predict the pattern of migration of the slowly varying invariants of motion, but the theory seems exceedingly abstract and it was not entirely clear that the features predicted are truly affecting particle motion in a real storage ring. Because of this, a campaign at the CERN SPS was undertaken and carried on from 2015 with a systematic approach to measuring the beam response to an ad-hoc excited third-order coupled resonance. The beam in the SPS is very small, and the energy is high enough to make the magnet ripples of small relative importance. The high energy also makes the beam self-fields and the indirect fields of negligible relevance. Therefore, the SPS pencil beam dynamics behaves very closely to that of a “single particle”. In the SPS the third-order resonance was excited with two sextupole magnets, to excite an arbitrary resonance driving term. The properties of the dynamics have been retrieved by measuring the beam position through two consecutive horizontal and vertical BPMs which are far apart by about 90-degree phase advance, and so it was possible to reconstruct the beam centroid orbits in the 4D phase space at a specific accelerator section. The results of the experimental campaign are summarized in Ref. [3], of which we show a highlight in Figure 85 in scaled coordinates. The visualization of the x, p_x, y, and py is clear only in 2D projections, of which Figure 85 shows a few. Note that the (x, p_x), and (y, p_y) planes exhibit no trace of the resonance, as the beam orbits are purely circular. The resonance instead appears in the mixed planes (x, y) or (p_x, p_y) with a specific correlation (so-called Lissajous curves).

The main feature of the coupled resonance is that resonant particles turn-after-turn jump on a closed curve in the 4D phase space (fixed-line), whose projections in 2D planes are those in IMG1. The confirmation of the existence in a particle accelerator of these nonlinear structures allows us to trust the computer simulations to predict the particle dynamics in this environment. The prediction of the fixed-line extension will allow the prediction of the particle beam migration and halo formation. This can be used to develop strategies to mitigate the effect of the resonance or to use it for a specific purpose [4]. Further experimental confirmation of the properties of the coupled third-order resonance, as the properties of unstable fixed lines, will be the subject of future investigations.

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9.13 High current ion source development at GSI

Authors: Aleksey Adonin, Ralph Hollinger

The development program on high current ion sources in 2023 was focused on the following three directions: investigation and overcoming the performance issues with Pb-208 cathodes [1], realization of high brilliance operation mode for high current Ar+ beam and development of new ion species for accelerator operation at GSI/ FAIR.

Investigation of performance issue of Pb-208

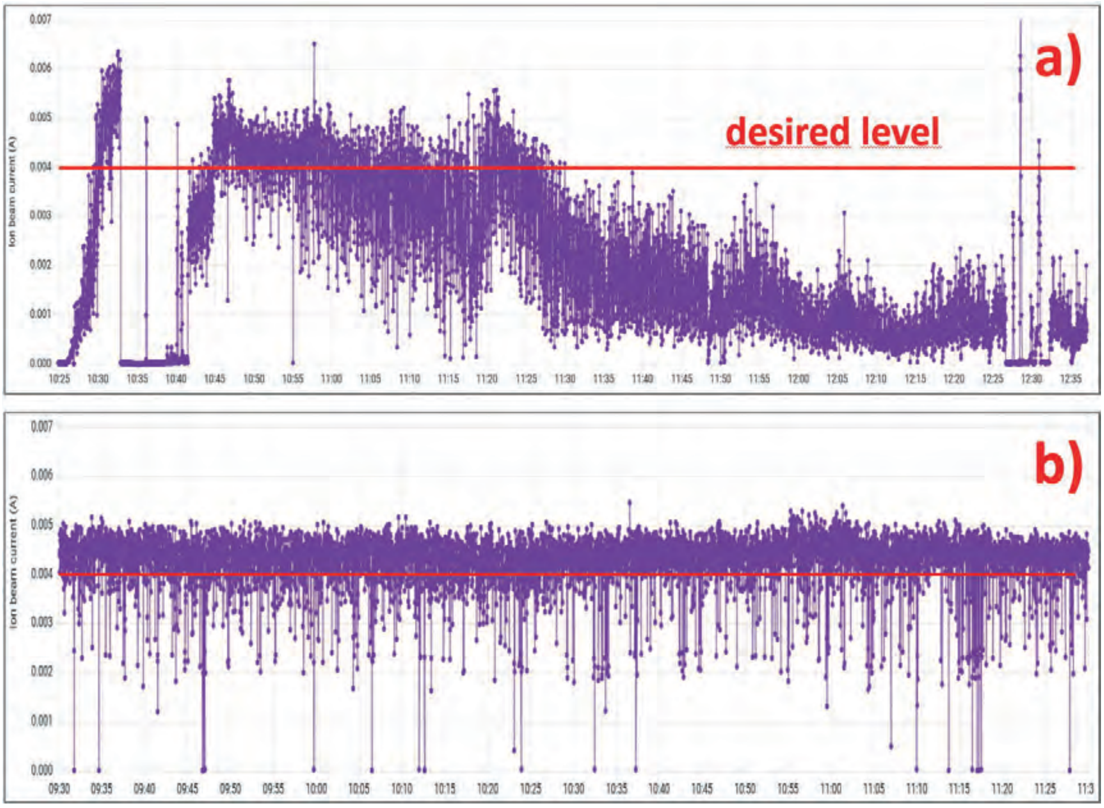


Figure 86. Operation stability of a $^{208}Pb^{4+}$ ion beam (current-time plot in front of the HSI-RFQ) over two hours with 1 Hz repetition rate: a) example of a "bad performing" Pb-208 cathode (from the manufacturing charge 2020) b) example of a "normal performing" Pb-208 cathode.

Operation of Pb-206 and Pb-208 from high current VARIS source are well established since 2018. For an efficient production of high intensity Pb^{4+} ion beam special composite cathodes Pb-Cu (40 % weight) are used in the ion source: litz-wire Cu structure filled with enriched Pb-206/Pb-208 material [2]. Such cathodes were manufactured by Fa. Hauner in several charges in different years. The cathodes with Pb-206 and Pb-208 from various charges produced in 2018 were successfully used in the beamtimes in 2020, in 2021 and in the first block in 2022, demonstrating stable pulse-to-pulse operation, high production efficiency of Pb^{4+} ions and a long-life resource of a single cathode (over 24 hours of operation). The second block of the beamtime in 2022 have been performed with the Pb-208 cathodes from a production charge of 2020. Unexpectedly, all cathodes of that production charge have shown the following behavior: a short conditioning time and a good performance (providing about 5 emA of Pb^{4+} ions in front of the HSI-RFQ) at the beginning of cathode operation (first 30 minutes) and then notable reduction of the beam intensity to 2-3 emA as well as an appearance of a strong pulse-to-pulse instability (Figure 86 a). After 2-3 hours of a cathode operation the beam current dropped to about 1 emA and the cathode must be changed to the new one.

In order to understand the reasons of bad performance of Pb-cathodes and to avoid this problematic in the future, a dedicated campaign of tests has been performed at the Terminal North during the shutdown in 2023. Manufacturing procedure of the Pb-Cu composite cathodes is rather complicated, it consists of several steps and have a few options. The influence of each step and option on the cathode performance has been checked in the ion source tests. Structure and geometry of the cathodes were investigated: twisted Cu litz-wire vs. parallel Cu litz-wire; 4 Cu-bundle vs. 5 Cu-bundle; influence of baking out the Cu litz-structure before melting of Pb; quality and form of enriched Pb-208 material: CAMPO vs. TRACE. As the result, the production process of the Pb-Cu composite cathodes was optimized and all tested cathodes from the last manufacturing charge (charge 2023) have demonstrated a good performance (Figure 86 b).

High brilliance operation mode for Ar$^+$

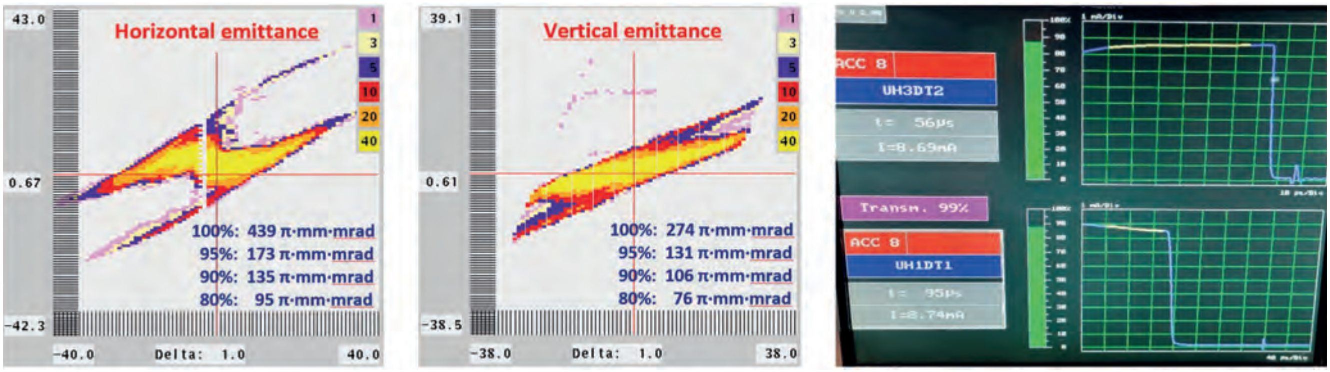
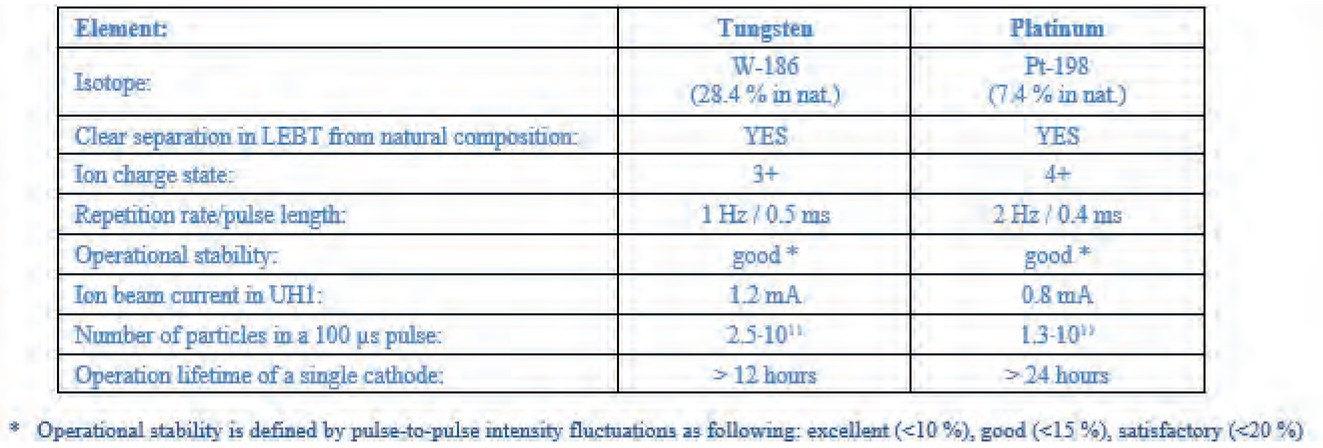


Figure 87. Beam emittance of high current Ar$^+$ beam from CHORDIS in front of the HSI-RFQ (left). Ion beam transmission through the RFQ (right).

In July 2023 during the shutdown in the high current injector (HSI) of the UNILAC the superlens was dismounted for reparation. That gave a unique opportunity to install a mobile emittance scanner and to measure beam emittances from both, high current and PIG ion sources directly behind the HSI-RFQ (the last opportunity of this kind was in 2011) [3]. During this measurement campaign a non-standard operation mode of high current Ar$^+$ beam provided from Terminal North by CHORDIS ion source was found. By using a long post-acceleration gap of 100-110 mm (instead of standardly used 40-60 mm) and special tuning of the beamline (LEBT) it was possible to reach the transmission of more than 95 % through the HSI-RFQ for 9 mA of Ar$^+$ ion beam (Figure 87).

Beam emittances for this operation mode have been recorded in front of as well as behind the HSI-RFQ. In Figure 87 the Ar-beam emittances measured in UH1-section in front of the RFQ in both: horizontal and vertical planes are shown. It was shown that such high brilliance operation mode is good reproducible. It is of the interest to check such a mode also for other beams especially for $^{238}U^{4+}$.

New ion species for operation



Element:	Tungsten	Platinum
Isotope:	W-186 (28.4 % in nat.)	Pt-198 (7.4 % in nat.)
Clear separation in LEBT from natural composition:	YES	YES
Ion charge state:	3+	4+
Repetition rate/pulse length:	1 Hz / 0.5 ms	2 Hz / 0.4 ms
Operational stability:	good *	good *
Ion beam current in UH1:	1.2 mA	0.8 mA
Number of particles in a 100 µs pulse:	$2.5 \cdot 10^{11}$	$1.3 \cdot 10^{11}$
Operation lifetime of a single cathode:	> 12 hours	> 24 hours

* Operational stability is defined by pulse-to-pulse intensity fluctuations as following: excellent (<10 %), good (<15 %), satisfactory (<20 %)

Figure 88. Table of test results for the new ion species from the VARIS.

A part of the ion sources research program in 2023 was dedicated to development of new ion species for the experiments. Two new ion species: $^{186}W^{3+}$ and $^{198}Pt^{4+}$ have been developed from high current vacuum arc ion source VARIS. The tests have been performed on the Terminal North and the HSI-LEBT during the shutdown in October 2023. The results of the tests are summarized in table in Figure 88.

For production of W-ions the cathodes out of an Elkonite (tungsten cupper composition) W85/Cu15 has been used due to manufacturing reasons. For injection into the HSI-RFQ the ion charge states of 3+ and higher are allowed for

W (M/Q ≤ 65). The production efficiency for W^{3+} ions in VARIS are considerably higher than for W^{4+} therefore the ion source and the LEBT were optimized for W^{3+}. Without the fine isotope separation in the LEBT it was possible to reach up to 7 emA of W^{3+} (all isotopes) in the UH1-section. That demonstrates the possibility to reach such beam current for the desired $^{186}W^{3+}$ ion beam in the case of using an enriched W-186 material. However, W^{3+} ions are intersecting with Cu+ ions by M/Q, thus fine separation of the W-isotopes is necessary. Amount of W-186 isotope in the natural composition is 28.4 %. By using the slits and fine tuning of the LEBT it was possible to clearly separate $^{186}W^{3+}$ ions from the rest and reach the beam current of 1.2 emA in UH1-section, that corresponds to $2.5 \cdot 10^{11}$ particles in a 100µs beam pulse. Tungsten has showed relatively stable operation with 1 Hz / 0.5 ms pulse length and pulse-to-pulse intensity fluctuations of about 15 %. The lifetime of a single W-cathode can be estimated as more than 12 hours.

A platinum-beam has never been provided by high current ion sources at GSI before. The lightest ion charge state accepted by the HSI-RFQ for Pt-198 is 4+. Maximum of ion charge states distribution for platinum in the ion source plasma is 3+. By conditioning of a Pt-cathode with the time the ratio of 4+ ions in the spectrum is increasing. Pt-198 is the heaviest isotope in the natural composition, it amounts 7.4 %. Using the slits as well as fine tuning of the beamline magnets in the LEBT it was possible to obtain a clear separation of Pt-198 in front of the RFQ. Platinum has demonstrated a stable operation by 2 Hz / 0.4 ms pulse length. The beam current of $^{198}Pt^{4+}$ beam reached 0.8 emA in UH1-section, which corresponds to $1.3 \cdot 10^{11}$ particles in a 100 µs pulse. The intensity fluctuations from pulse to pulse were not exceeding 15 %. The first test with platinum was quite successful, however there are ideas how to improve the VARIS performance with Pt^{4+} ions. Further tests are planned for 2024.

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9.14 ECR Ion Source ion source development at GSI

Authors: Fabio Maimone, Aleksandr Andreev, Michael Galonska, Ralf Lang, Jan Mäder, Patrick Patchakui

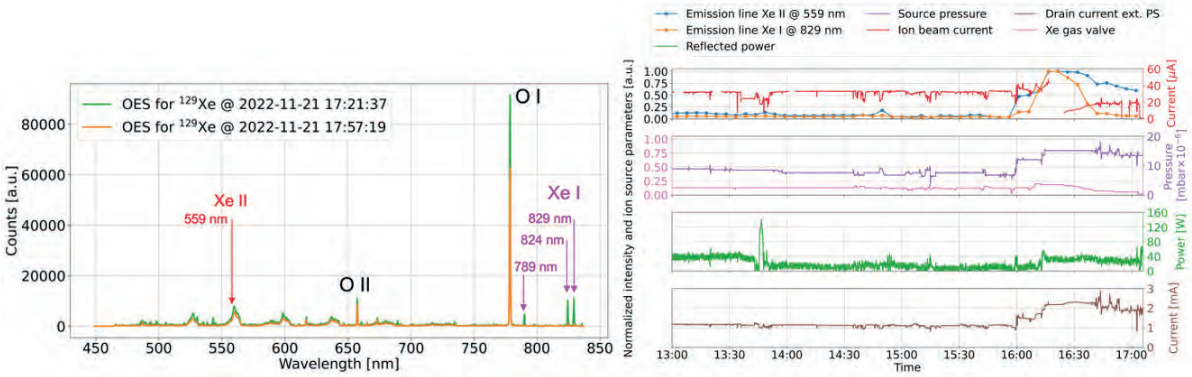

Figure 89. OES measurements for xenon (left) when the ECRIS is optimized for Xe^{18+}, Xe^{23+}, and time [hh:mm] variations of xenon spectral lines at 559 and 829 nm (right) together with the ECRIS settings.

At GSI the CAPRICE ECRIS is in operation to deliver high-charge state ion beams from gaseous and metallic elements to the accelerator facility. A test campaign has been carried out at the ECR test bench to fulfill the demand for higher intensity and stability of high charge state ions and mixed ion beams with the support of an Optical Emission Spectrometer (OES) from Ocean Insight as a monitoring tool. The main parameters and settings of the ECRIS during operation have been continuously recorded: the valve setting of the main gas, the reflected microwave power level, the ECRIS ion source pressure, the ion beam current measured after the dipole magnet and the drain current of the extraction power supply. The analysis of the time variations of spectral lines together with the ECRIS settings has been related to the intensity of the extracted ion beam to monitor the ion source stability. The experimental campaign has been performed with noble gases and with oxygen as a support gas. Since no plasma instabilities were observed with the above-described experimental setup previously described during this experimental campaign, it was decided to stimulate their appearance by actively changing the source parameters. Therefore, the present analysis focuses mainly on the periods when the source optimization was performed to evaluate the effect of the parameters change on the ECRIS and the visible spectral content. As soon as the ECRIS was optimized for the desired charge states, the optical emitted spectra in the visible wavelength range were saved. The optical emission lines of each element (neutral and 1+ ion) were identified using the NIST database [1] and the time variation of the lines was monitored and saved. Figure 89 shows the OES measurement for xenon (left) when the ECRIS was optimized for Xe^{18+}, and Xe^{23+}, respectively. Figure 89 (right) shows the time variations of the xenon spectral lines at 559 and 829 nm together with the ECRIS settings. Two ion source settings were selected to maximize the intensities of two different charge states: Xe^{18+} and Xe^{23+} beams. The setting change can be noted at 16:25 in Figure 90 (left).

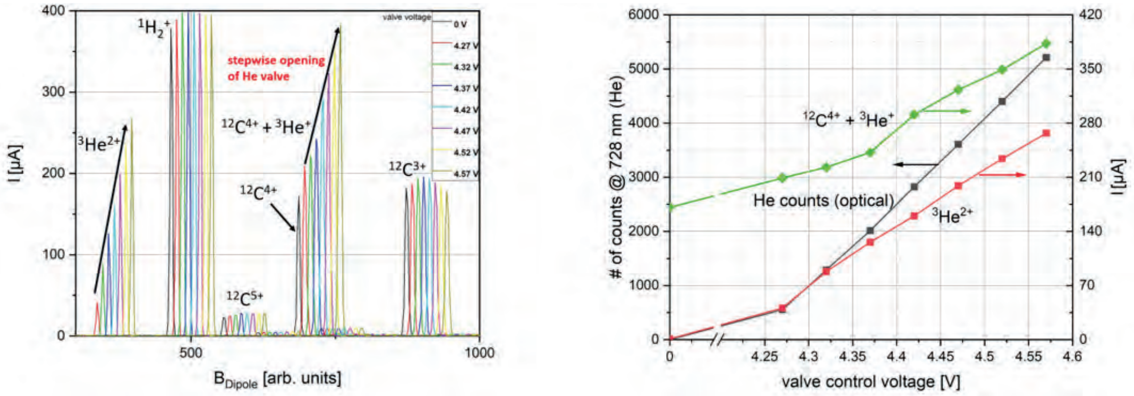

Figure 90. Spectra for CH_4 + ^3He (left) and ion intensities and emission line at 728 nm (right) for He valve stepwise opening.

The analysis of this figure shows that the intensity of the measured emission lines increases with the gas pressure thus affecting the microwave power to the plasma coupling, as well. The analysis of the data obtained for the noble gases together with the intensity of the measured optical emission lines allows us to conclude that the ion source operation and the optical lines remain stable if the ECRIS settings are not adjusted.

In the context of fundamental research in carbon ion beam therapy, a mixed carbon/helium ion beam has to be provided to the users. The request is a steady carbon ion beam of approximately 150 eμA ($^{12}C^{3+}$ or $^{12}C^{4+}$) containing a helium particle fraction of about 10 %, i.e. approx. 5 eμA ($^{4}He^{+}$ or $^{3}He^{+}$) in front of the subsequent linac-synchrotron accelerator chain. For the experimental test carried out at the test bench, a C^{4+} ion beam was set and followed by stepwise adding helium to the plasma while recording the optical emission lines and the corresponding mass spectra. Since there is no distinction between $^{12}C^{4+}$ and $^{3}He^{+}$, the optical emission lines of carbon (wavelength 465 nm) and helium (728 nm) allow for an estimate of the C-to-He ratio. As the He I peak at 728 nm wavelength increases with the stepwise opening of the He-valve, the combined $^{12}C^{4+}/^{3}He^{+}$ peak and $^{3}He^{2+}$ increase in the mass spectrum as well (IMG2, left). Thus, it is possible to establish a relation between increasing current in the combined peak and the optical emission lines (Figure 90, right), but not yet giving the absolute number of particles. [2] According to the results achieved at the test bench, the mixed carbon/helium ion beam has been successfully established at HLI for the engineering run.

Acknowledgments

The OES measurements were carried out in the framework of ERIBS (European Research Infrastructure – Beam Services) collaboration within the EURO-LABS project funded by the EU´s Horizon Research and Innovation programme (Grant Agreement n° 101057511).

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9.15 Post Stripper Upgrade (PSU) - Series procurements for the new post-stripper DTL Alvarez 2.0

Authors: Sascha Mickat, Lars Groening, Manuel Heilmann, Michael Kaiser, Michael Maier

The existing post-stripper drift tube linac (DTL) of the UNILAC has been in operation for more than 45 years. In 2012, a dedicated report on its state and perspectives drew attention to increased failure rates and downtimes from significant aging. Additionally, its design from the 1960ies does not foresee intense beams of heavy ions as being mandatory for FAIR. The project “Alvarez 2.0” was started in 2017 with a dedicated first-of-series (FoS) cavity section, which represents the first two meters of the planned 55-meter long and new DTL. The FoS was tested without a beam successfully by operating far beyond the nominal RF parameters.

The tendering of series components has been started in parallel to the tests, such that immediately after the successful test campaign, the first order for series components has been placed. In early 2022, the 25 tank sections and 10 cavity end plates were ordered, as the DTL comprises five cavities (AI, AIIa, AIIb, AIII, and AIV), each of five sections and two end-plates [1]. Main activities in 2022 and 2023 were targeting at series procurements. Diverse add-on parts and the 52 drift tubes with integrated quadrupole lenses for cavity AI were tendered and ordered. In addition, and to qualify a second supplier for drift tubes, a study for the longest drift tube, at the exit of cavity AIV, was tendered. In December 2023, the order of the 40 drift tubes of cavity AIIa was placed.

- [1] L. Groening et al., Starting series production of the new UNILAC post-stripper DTL Alvarez 2.0, ch.9.15, p.124ff, In: GSI Scientific Report 2022

Highlights in 2023

Figure 91. Tank sections of cavities AI and AIIa at the supplier (left) and one of the four end plates after mechanical polishing (right).

The series production of the 25 tank sections and 10 end plates and their delivery have been delayed at request of GSI for two reasons: areas for storage on Campus were occupied with FAIR-related components and the re-commissioning of the on-site GSI galvanic workshop was delayed. The five sections of AI with the two end plates were accepted at the site. The big components for cavity AIIa are nearly ready to deliver, the production for cavity AIIb is advanced [Figure 91 and Figure 92].

The big components are planned to be Cu-plated at the GSI galvanic workshop. Plating of the tank sections and end plates of the Alvarez cavities at the GSI galvanic workshop was shifted to 2024. Smaller parts as drift tubes and add-on parts shall be Cu-plated externally. A market analysis revealed that there is no industrial supplier to Cu-plate the nearly 200 drift tubes. Therefore, an agreement with CERN has been signed for plating the drift tubes at CERN’s galvanic workshop.

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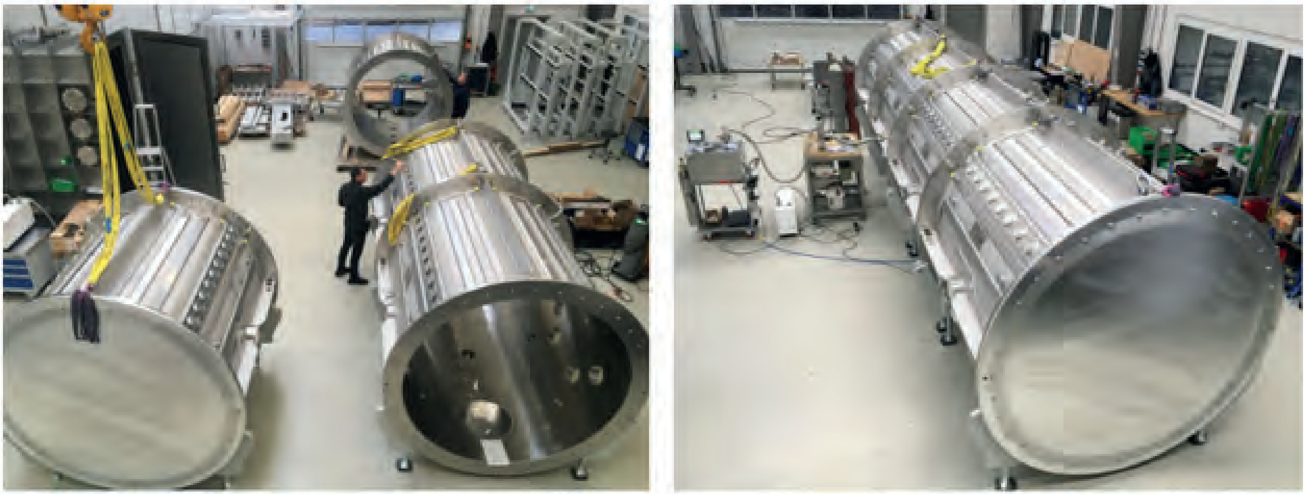

Figure 92. Tank sections of the cavity AI during the factory acceptance test.

For the production of the drift tubes for cavities AI and AIIa, two suppliers were awarded. One supplier has already completed prototyping successfully and will start immediate series production of the series for cavity AIIa. The other partner prepares series production by developing the prototype of the longest drift tube assigned to cavity AIV [Figure 93 left].

Figure 93. Single components of the longest AIV drift tube as part of a study (left). Successful tests of the shortest drift tube without housing (mid) and with housing (right) in pulsed operation mode.

The five Alvarez cavities are connected by four inter-tank sections. Due to the requirements on beam quality for intense heavy ions beams, the installation length is very limited, although various diagnostics, three quadrupole lenses, and a re-buncher have to fit into the section. The re-buncher shall be integrated at a later stage. A dummy (a simple vacuum pipe) fills in its position. Development of very compact beam diagnostics devices is in progress. A combination of a diagnostic chamber and an integrated phase probe as a prototype was procured [Figure 94 right].

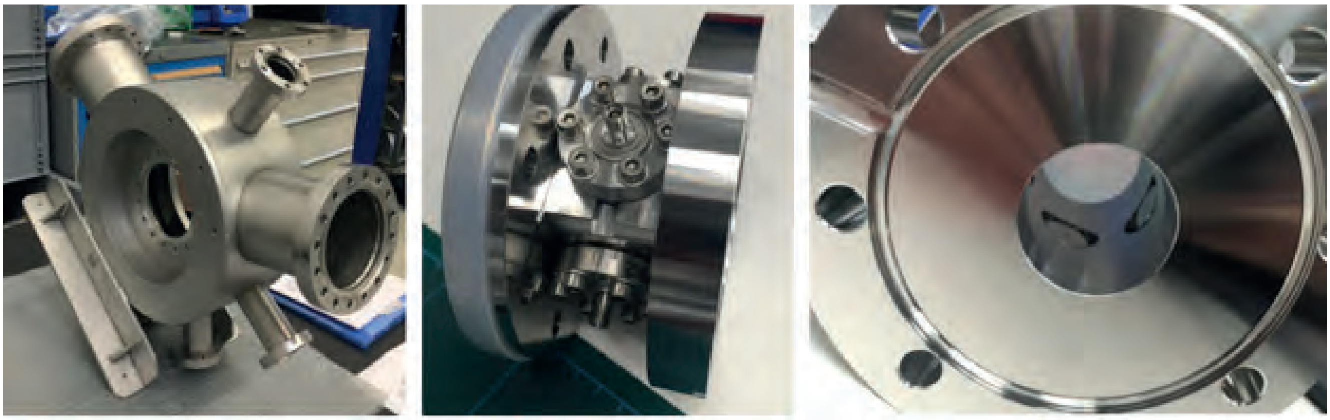

Figure 94. Developed diagnostic chamber with a compact design for the inter-tank sections (left). The phase probe (mid) with four separated pick-ups (right) is integrated into the chamber.

Outlook for 2024

In 2024, the remaining 20 tank sections and eight end plates shall be delivered cavity-wise following a three-month rhythm. Also, the Cu-plating of the tank sections at the GSI galvanic workshop shall start. Currently, huge efforts are being made to provide adequate storage areas within GSI's neighborhoods. Areas on campus, currently in use as storage areas for FAIR components, could be emptied and used for pre-assembly and testing of the Alvarez cavities.

Concerning the drift tubes, two major milestones are expected to be reached in 2024: completion of prototyping of the longest drift tube and starting production of drift tubes for the series at both suppliers. Tendering the remaining drift tubes of cavities AIIb to AIV is linked to the provision of a budget beyond 2025, which has to be released by the BMBF. The GSI supervisory board (Aufsichtsrat) strongly supports this application for budget beyond 2025 and the decision is expected in June 2024 at the earliest. Simultaneously, procurement of several add-on parts for the series is ongoing together with Cu-plating at external workshops.

9.16 Rf-field mapping of linac cavities with falling beads

Author: Xiaonan Du

The bead-pull method, grounded in Slater's small signal perturbation theory, posits that introducing a small bead, whether metallic or dielectric, into a resonant cavity causes a shift in the resonant frequency away from its original value. This shift is directly proportional to the combined squared magnitudes of the electric and magnetic fields at the bead's location. Employing a pulley and wire system, this method facilitates the movement of a bead through the cavity, enabling the measurement of the radio frequency (RF) field along its path. It is a prevalent technique for examining field distribution and tuning in various types of cavities.

In pursuit of an innovative approach, we have been developing what we term the bead-falling-measurement method. This technique leverages the free fall of a bead to induce perturbations, thereby eliminating the need for a pulley-wire system and its associated complications. This method presents a promising alternative to the conventional bead-pull measurement, offering several advantages. Over the past two years, we have put dedicated efforts to establishing both the hardware and software components of this method. Utilizing the compact Raspberry Pi 4 as a controller for the Vector Network Analyzer (VNA) and as a data collection tool, this system demonstrates the feasibility of running the software on a portable device. Water droplets, employed as the perturbing agents, are generated continuously and traverse the cavity at high velocities, enabling swift, repeated measurements. A laser and light sensor duo is employed to detect the falling droplets, marking the commencement of each measurement. Various experiments have been conducted to optimize the prototype device, with measurements taken from two distinct types of RF cavities.

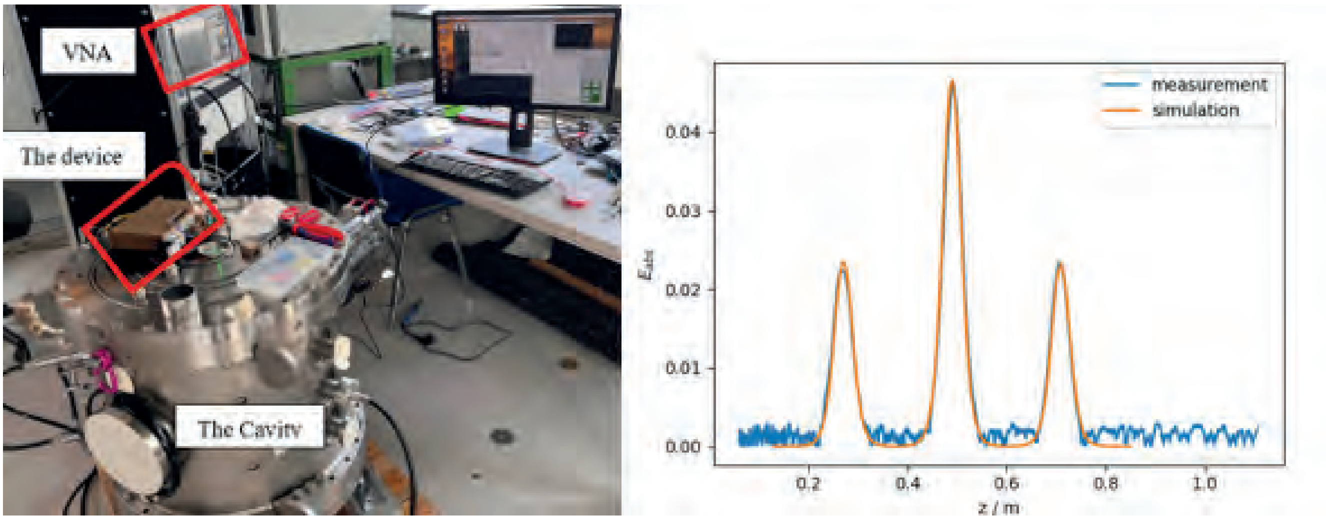

Figure 95. Left: the site for bead-fall measurement of BB3; Right: The measured field distribution along beam axis compared with simulation.

The 36 MHz buncher BB3, designed for beam injection into the UNILAC post-stripper, represents one of the newly delivered cavities set to replace the existing BB3 unit. The cavity's orientation aligns the beam axis with local gravity, with the measurement apparatus mounted atop the cavity along the beam axis. The test setup is depicted in Figure 95 (a), and the subsequent field distribution measurements obtained via the bead-falling method, as illustrated in Figure 95 (b), demonstrates a good agreement with simulation results.

The measurement process was similarly applied to a model cavity, specifically a 1:3 scale aluminum replica of an Alvarez-type cavity, as part of a comprehensive upgrade initiative at the UNILAC. This scaled-down version of the Alvarez model primarily served to explore the stabilization strategy, focusing on tilt sensitivity. Despite the initial data being heavily loaded with noise attributed to the soft coupler, we successfully discerned the field distribution. The ability to perform rapid, iterative measurements facilitated the accumulation of a substantial dataset in a brief timeframe. This wealth of data enabled us to employ Singular Value Decomposition (SVD) techniques to filter out noise and accurately ascertain the field distribution, as depicted in Figure 96.

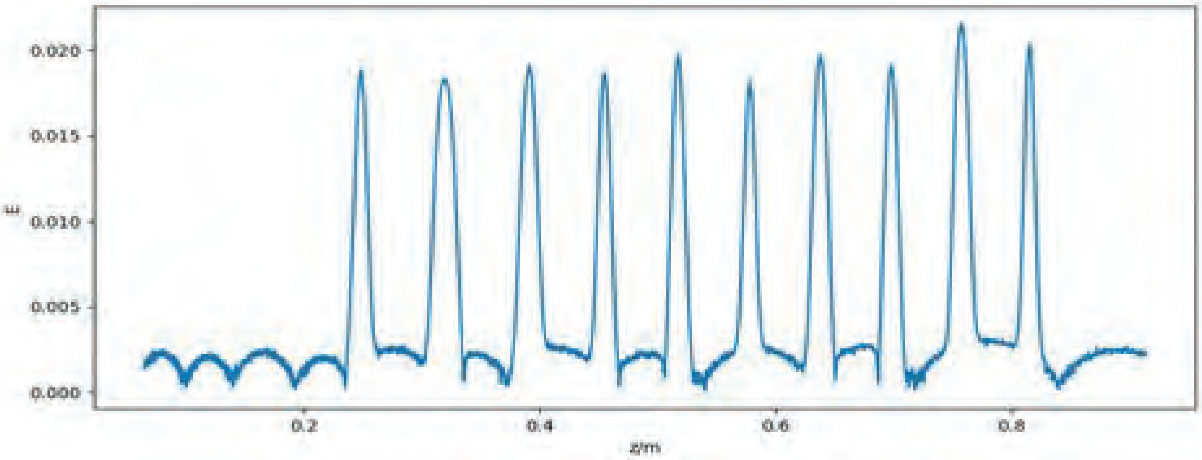

Figure 96. **The measured electric field distribution of the scaled model cavity along beam axis.**

9.17 Complete 4D-matching of intense coupled hadron beams

Author: Chen Xiao

Preservation of beam quality is of major concern for acceleration and transport especially of intense hadron beams. This aim is reached at best through provision of smooth and periodic beam envelopes, being so-called matched to the periodicity of the external focusing lattice. This is fully sufficient as long as there is no coupling between the phase space planes (for brevity planes), neither in beam properties nor in lattice properties.

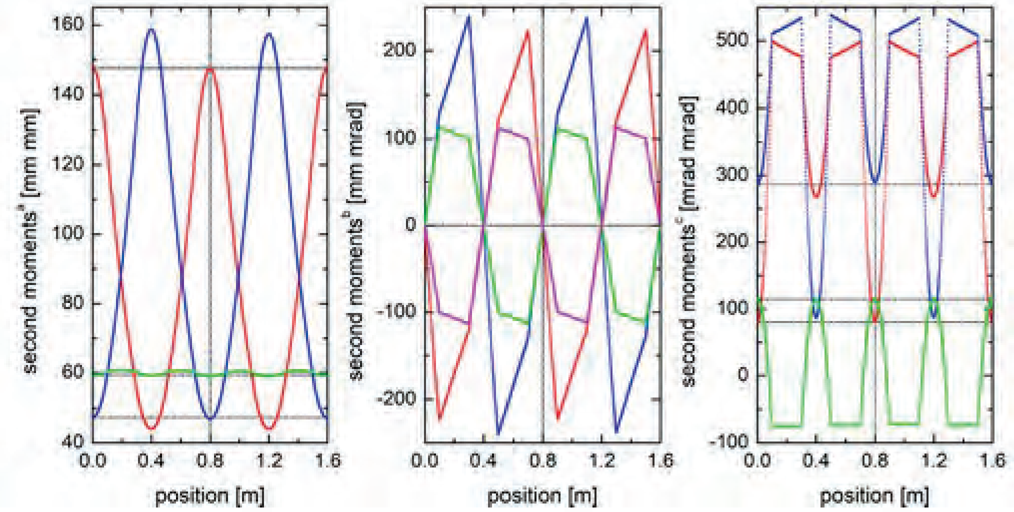

Figure 97. Full 4D-periodic solution: the ten independent rms-moments along the regular quadrupole channel (two cells) for acoupled proton beam with 10 mA at 150 keV. Left: rms-moments <xx>, <yy>, and <xy> (red, blue, and green); Middle: rms-moments <xx'>, <yy'>, <xy'>, and <x'y> (red, blue, green, and magenta); Right: rms-moments <x'x'>, <y'y'>, and <x'y'> (red, blue, and green).

For beams without coupling, various matching methods for intense beams have been proposed and realized in operation. The presented work is on the development and demonstration of a method to determine a solution for four dimensional (4D) rms-matched transport of intense beams with considerable transverse coupling. Through simulations it has been shown that the lattice periodicity is not just matched by the two transverse envelopes but also by the beam rms-moments that quantify coupling. To this end, an iterative procedure towards the periodic solution is applied. It starts from determining the solution with zero current, using a method that is applied later also to beams with current.

For zero current, the effective focusing forces are given solely by the external lattice. The actual beam shape has no influence on them and therefore the periodic solution even for coupled beams may be found analytically. For intense beams instead, defocusing space charge forces depend on the beam shape and orientation in real space. Actually, they depend also on the spatial distribution type. Figure 97 shows the full 4D-periodic solution of an intense and coupled proton beam to a lattice comprising regular quadrupoles (FODO-type).

It has been shown that a cell-to-cell full 4D-periodic solution can be determined for a coupled beam with considerable space charge forces. This has been accomplished by rms-tracking of coupled beams with KV-distribution combined with a dedicated iterative procedure of tracking and generic re-matching. Full 4D-periodicity of the beam revealed to suppress growth of the 4D emittance much better w.r.t. simple 2D-envelope matching.

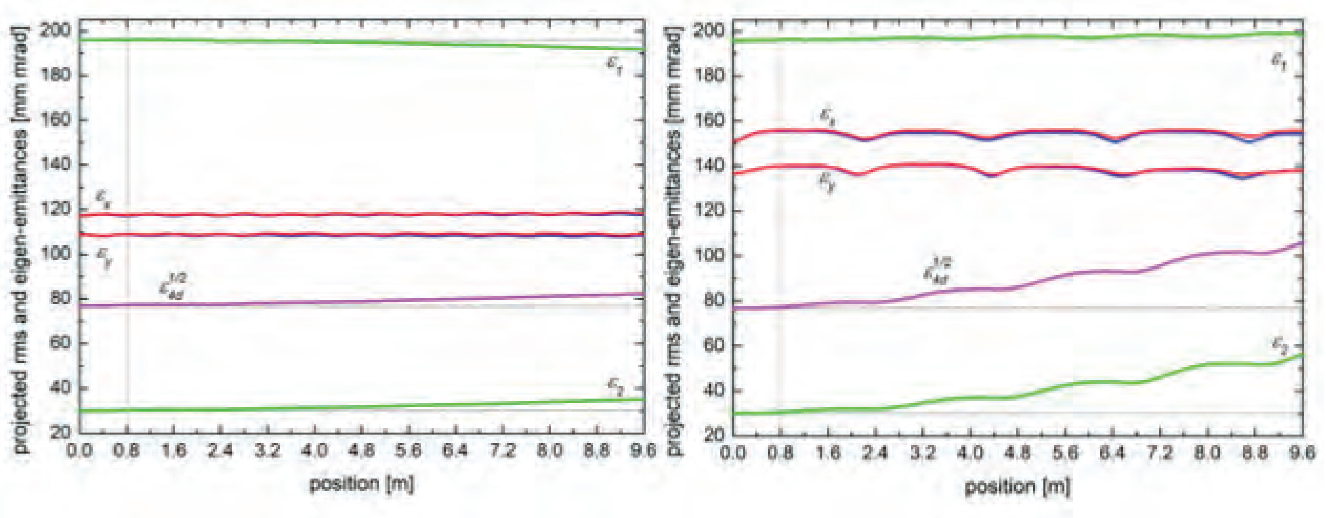

Figure 98. Left: emittance growths from 2D-envelope matching along the regular quadrupole channel (12 cells) for a coupled proton beam with 10 mA at 150 keV; Right: corresponding emittance growths from 4D-moment matching. Red and blue curves indicate the projected rms-emittances; Green curves indicate the eigen-emittances; Magenta curves indicate the production of two eigen-emittances.

9.18 Deceleration of ions at HITRAP

Authors: Z. Andelkovic, F. Herfurth, N. Stallkamp (GUF), W. Geithner, S. Fedotova, S. Rausch (TUDA), S. Trotsenko, M. Horst (TUDA)

The heavy ion decelerator and trap HITRAP [1] serve as a vital resource for precision experiments involving low-energy highly charged ions (HCI). The facility operates through two primary mechanisms: deceleration of ions from the GSI accelerator complex and local production of HCI using an electron beam ion trap (EBIT). HITRAP exhibits three distinct groups of activities:

While no formal beamtime period was scheduled, the accelerator facility, comprising several high-frequency (HF) stages and corresponding instrumentation for in-flight ion beam deceleration, was part of the engineering run. This period was utilized for critical tasks, particularly the operation of the IH and RFQ cavities, yielding control-RF voltage surpassing 7 V with proper sinusoidal waveforms. The physics model of the facility was upgraded to include warming pulses for the RF cavities at intermediate amplitudes, necessary for stable operation without overheating the elements. These endeavors were vital in preparing for upcoming beamtimes. The FAIR CS saw an expansion to include the low-energy beamline between the RFQ and the cooling trap, enhancing overall functionality and control. Additionally, the local EBIT continued its routine operations, supplying ions for local testing purposes.

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, electrostatic beam focusing elements and differential pumping barriers. Several tasks were completed in the course of the shutdown period. The local, LabVIEW-based control system was expanded with a slow control to operate the ion optical elements in a predefined timing sequence. These efforts enabled sending ions from the EBIT to the cooling trap and the subsequent ejection in the direction back towards the EBIT, enabling separation of charges of trapped ions and simulating the envisaged beamtime operation. Also a vacuum baking system was reinstalled to improve the residual gas pressure in the vicinity of the Penning trap and reinforced by adding NEG pumps. Beside regular hardware maintenance of vacuum equipment and power supplies, also preparations for further expansion of the control system from LabVIEW to FAIR CS are still ongoing. This includes an upgrade of the ion beam diagnostic hardware and the installation of the CUPID software, both of which took place and saw first tests with beam. Finally, a simple motor design was adapted from the CRYRING facility to serve diagnostic elements at HITRAP, without the need for a full stepper motor system.

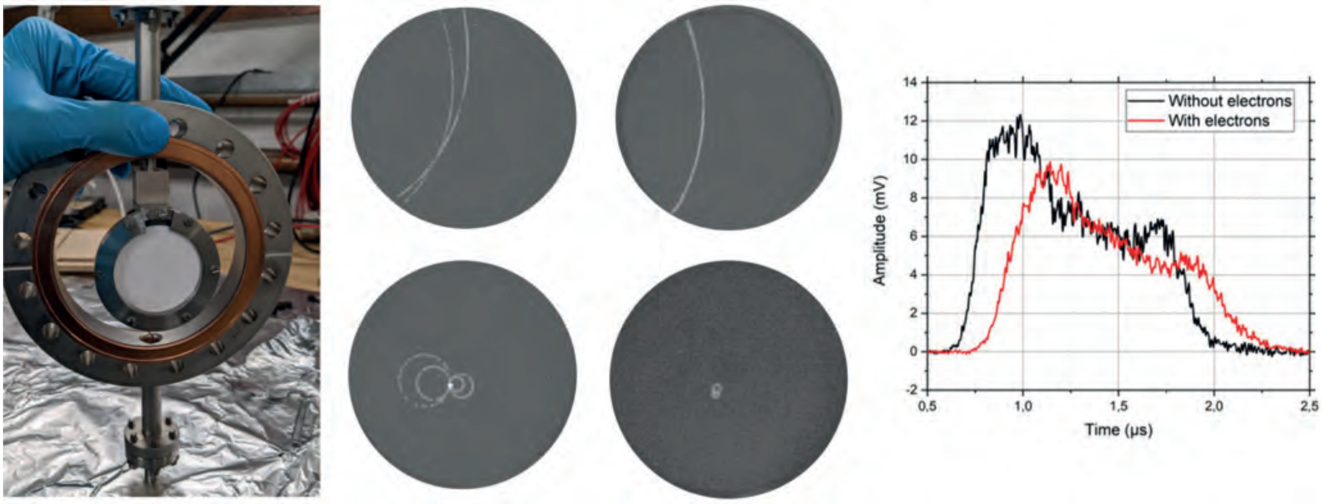

Figure 99. Left - a retractable phosphorus screen for beam imaging. Middle - four images of ejected electron plasma, showcasing the trap alignment process, which led to the observation of ion cooling by electrons. Roght – TOF of trapped ions with and without cooling, demonstrating the energy loss.

Cooling of trapped ions comprises a Penning trap in a superconducting magnet, remains the most challenging part of the project [2]: the trap is designed to capture HCI and enable energy transfer to simultaneously stored electrons, which dissipate it by emitting synchrotron radiation. A significant milestone was reached with the installation of a novel detector for imaging electrons stored in the cooling trap. This advancement significantly improved the alignment of the trap with respect to the magnetic field, laying the groundwork for subsequent achievements. This is illustrated in Figure 99. The cooling trap itself achieved a major breakthrough by demonstrating cooling of

HCI from the local EBIT. Through meticulous alignment and optimization, ions were stored and efficiently cooled within a few seconds, validating theoretical models and enhancing confidence in the capabilities of the trap. These successful outcomes paved the way for HITRAP's readiness for the anticipated beamtime in the year 2024, marking a significant step forward in its operational objectives. Efforts are ongoing to monitor the cooling process non-destructively, as well as to eject the ions towards the experiment installations further downstream.

Outlook for 2024

For the beam time 2024, two periods are scheduled for further commissioning of the facility. They foresee the online ion signal in the low-energy beam transport section as well as HCI inside the cooling trap. Both steps are essential towards the GPAC approved experiments with surface modification by HCI impact and the spectroscopy of HCI. Furthermore, within the framework of a new Helmholtz young investigator group, a new laboratory space close to the HITRAP facility is under construction, with the perspective of utilizing heavy HCI as novel frequency standards, a world-wide unique setup with unprecedented accuracy.

References

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- [2] S. Rausch, et. al.: Commissioning of the HITRAP Cooling Trap with Offline Ions, Atoms 10, 142, (2022), DOI:10.3390/atoms10040142

9.19 HELIAC CM1 commissioning

Authors: Maksym Miski-Oglu, Florian Dziuba, Viktor Gettmann, Thorsten Kürzeder (GSI, HIM),
Christoph Burandt, Simon Lauber, Julian List, Stepan Yaramyshev,
Winfried Barth (GSI & HIM)

Figure 100. The CH0 cavity is lowered into the US bath using a special lifting frame (left). The solenoid S1 is set up in the HPR cabinet, aligned and prepared for rinsing (center). The power coupler is mounted to the coupling port of CH0 (right). All the activities shown carried out in the cleanroom laboratory at HIM.

Since the end of 2022, the cold-string of the Advanced Demonstrator, which serves as a prototype cryogenic module (CM) for the future continuous wave (cw) linac HELIAC (HElmholtz LInear ACcelerator) at GSI, has been under construction. The standard cryomodule CM1 is equipped with three superconducting (SC) Crossbar H-mode (CH) cavities CH0-CH2 with maximum design gradients up to $E_{a,\ design}$ = 7 MV/m, a SC buncher (B1) cavity with $E_{a,\ design}$ = 5 MV/m, as well as two 9 T SC solenoids (S1, S2). To avoid contamination with dust particles, the SC components were assembled in the ISO-class 4/6 cleanroom laboratory at Helmholtz Institute Mainz (HIM). For this purpose, each individual component, including all nuts, screws, bolts or seals, was thoroughly cleaned in an ultrasonic (US) bath and then conductively rinsed with ultrapure water (see Figure 100 left). As can be seen in Figure 100 (center), particularly critical components such as the cavities, solenoids, parts of the power couplers or beam pipe bellows were additionally treated with high-pressure rinsing (HPR). Figure 100 (right) shows the assembly of the power coupler antenna with the cold window part to cavity B1. In March 2023, all work was completed and the cold-string was successfully transferred out of the in the cleanroom environment after intense leak checking.

Figure 101. Fully assembled cold-string inside the segmented support frame, which is mounted on a rail system. This design enables smooth integration of the cold-mass into the cryostat. Here, the beam entrance is on the left-hand side of the cold-string.

Outside the cleanroom, the cold-mass was wrapped with multi-layer insulation foil and the cavities were provided with a magnetic μ-metal shielding. In addition, the tuner drives, consisting of a stepper motor for slow and a piezo actuator for fast frequency tuning, were added to each cavity. Several RF measurements have been performed to adjust the external coupling strength Qext and the tuning range df/dx of the dynamic bellow tuners. In order to achieve a sufficiently high bandwidth (up to 200 Hz) for stable operation, Q_{ext} has been set in the range of 106 for all cavities. The maximum achievable tuning range varies between df/dx = ±37 kHz/mm (for CH0) and df/dx = ±110 kHz/mm (for CH2) due to the slightly different bellow tuner geometry of the individual cavities. In a next step, the string was attached to the segmented support frame using a nuclotron suspension system. After aligning all components to the beam axis with an accuracy of ±0.2 mm using laser tracker, the segmented frame was integrated into the cryostat. Figure 101 shows the fully assembled segmented support frame in preparation for cryostat integration. At the end of May 2023, CM1 was completed with all necessary auxiliaries for 4 K commissioning and transported from HIM to GSI.

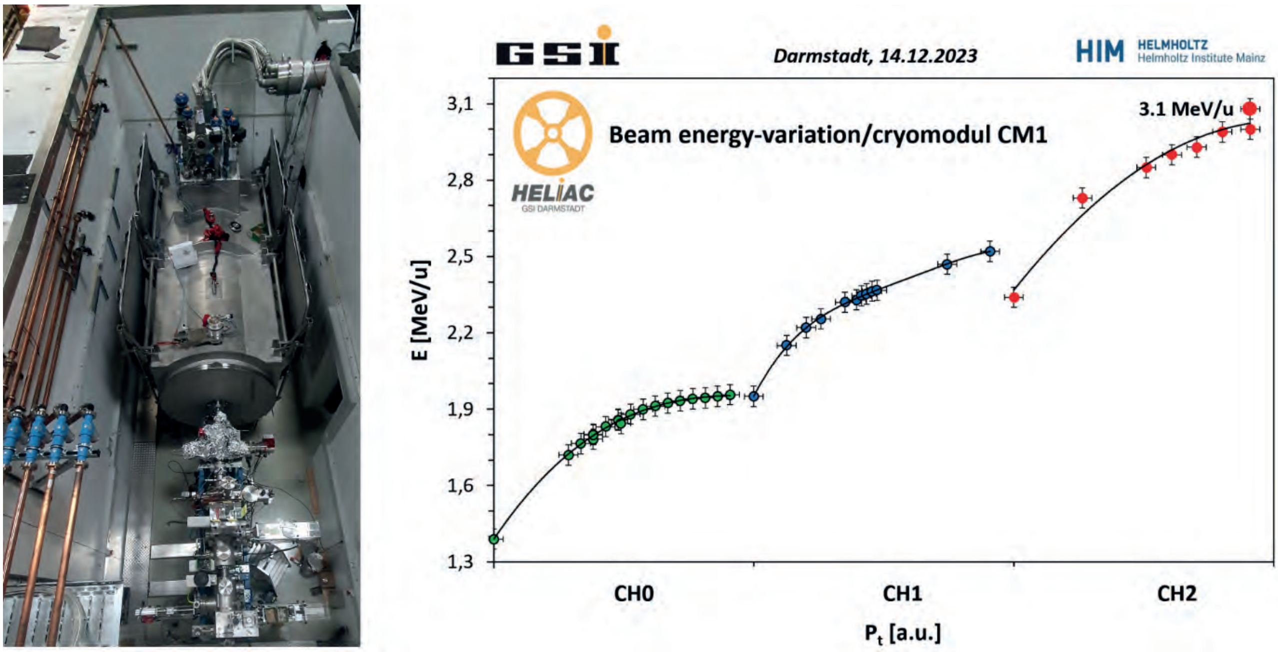


Figure 102. Left panel shows the first cryogenic module inside the test bunker at GSI. It is integrated into beamline and connected to cryogenic supply. Right panel shows the measured kinetic energy of accelerated He^{2+} ion beam.

The fully equipped cryogenic accelerator module CM1 was transported to GSI. The alignment of the accelerator components after transport was checked with a laser tracker and transferred to the outer shell of the cryostat. The alignment of the components survived the transport without changes. The differential pump stage, each consisting of two chambers protects the vacuum inside the cryogenic module and generates the vacuum pressure gradient from 10^{-7} mbar in the matching line to 10^{-10} mbar within the module. The vacuum system was installed under the mobile clean room tent to avoid possible contamination by dust particles. The left panel of Figure 102 shows the cryogenic module installed in radiation protection shelter.

The test area is connected to the cryogenic plant of the GSI series test facility (STF). The cryogenic distribution system at the test area is in operation since 2020. In preparation for beam testing activities, the beamline connecting the High Charge State Injector (HLI) to the test area was installed and beam tested in 2021. The matching beamline consists of a pair of phase probes for time-of-flight (TOF) measurement of the incoming beam energy, quadrupole lenses for transverse machining and a 4-gap RF buncher cavity for longitudinal matching. The beam diagnostics bench behind the cryostat is equipped with a pair of phase probes to measure the output beam energy, a slit grid to measure the transversal beam emittance and a Feshenko Bunch Structure Monitor (BSM) to measure the longitudinal beam profile. This setup allows a complete 6d characterisation of the ion beam. All beam instrumentation was commissioned with beam prior to cooling down of the cryomodule. The local helium distribution system and the radiation shielding of the cryostat were cooled in less than two days and were ready for the cooling of CM1. After cooling of the radiation shield, the temperature of the RF cavities was 220K. In the temperature range from 150K to 50K, niobium hydride (NbH5) can form on the RF surface of the cavities and lead to so-called Q-disease, a dramatic degradation of the quality factor. To avoid the formation of NbH5 on the rf surface of the superconducting cavities, they should be cooled at a cooling rate of 1K/min. The liquid helium from the DB01 distribution box was injected into the 4K system of the cryomodule. The achieved cooling rate of 0.6 K/min was slower than intended. The main limitation is due to the maximum design absolute pressure for RF cavities of 1.5 bar and the inlet pressure at the quench buffer of the STF. After a cooling period of approximately 12 hours, the RF cavities are completely immersed in liquid helium. RF conditioning of the four cavities was performed sequentially using two vector network analysers (VNA). The forward RF power provided by 3kW RF amplifiers was gradually increased until the multipacting barriers disappeared. For further conditioning and measurement of the acceleration gradient, the cavities were operated in phase-locked loop mode. In this mode, the RF generator tracks the resonant frequency of the superconducting cavity, which varies strongly with pressure in the 4K He-system of the cryostat. The pressure fluctuation of 1 mbar in the He-system leads to a change of the resonance frequency of about whole band-width of the cavity. The design acceleration gradient of the CH0 cavity is 5.5 MV/m, it reached a maximum of 6 MV/m during rf conditioning and was limited by thermal quenching. The design gradient for the CH1 and CH2 cavities is 6.5 MV/m. They reached maximum gradients of 8.5 MV/m and 12.5 MV/m respectively, well above the design. These cavities are equipped with a mue-metal shield against the earth's magnetic field. Due to lack of time and budget, CH0 was not equipped with a metal shield, which is probably the reason for the relatively low maximum gradients. Direct measurement of the quality factor Q of the cavities was not possible due to the high coupling factors, well above 100, required for stable operation with beam. A reliable measurement of the reflected RF power is not possible at such high coupling factors. The dedicated cold campaign to measure the quality factor as a function of the accelerating gradient is planned for mid-2024.

A generator-driven system with a constant master frequency was used for beam operation. In this mode, the resonant frequency of the cavity is kept constant by a piston tuner driven by a piezo actuator. The amplitude and phase of the cavities are controlled by the same analogue low level RF system as the normal conducting cavities of the existing UNILAC.

In this mode the pondermotive instability of the feedback system plus cavity occurred unexpectedly. Stable operation of the cavities was only possible with a gradient of up to 2MV/m. The reason for this instability is probably due to the choice of too small a bandwidth for the cavity and will be the subject of further investigation. This limitation of the acceleration gradient leads to a limitation of the mass-to-charge ratio $A \leq 2$ for accelerated ion species. For this reason, the ion source of the HLI injector was operated with double ionized helium He^{2+}.

On 14 December 2023 at 19:04, the time had come: After five years of development, construction and commissioning, the helium beam was accelerated to 3.1 MeV/u for the first time in the HELIAC cryomodule CM1. The right panel of Figure 102 shows the measured kinetic energy of the accelerated beam as a function of rf power at the pick-up probe of the corresponding cavities. Further investigations with beam are scheduled for June 2024.

9.20 FAIR test automation in GSI-environment

Authors: Oksana Geithner, Arthur Halama, Stefan Krepp, Stephan Reimann

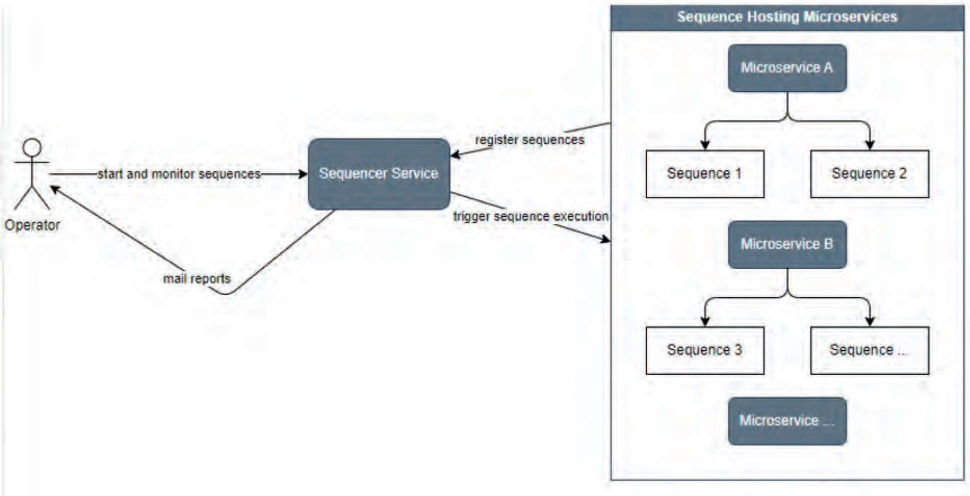


Figure 103. Software architecture of the sequencer tool.

The operation of the accelerator demands a significant amount of manpower. Control system tools could streamline and take over repetitive tasks during commissioning and beam time, such as device scanning, beam optimization, or device steering. The larger the accelerator facility and the number of identical devices, the greater the benefits of automating various task procedures. To address this need, a sequencer tool has been developed at GSI.

Possible Use Cases

As the steering of included devices is automated, one could consider all possible hardware (HW) manipulations and use case combinations. Here, we present the most common ones we started with:

- Switch remote power on/off chosen facility area.
- HW commissioning
- Switch on/off power saving mode in case of longer accelerator failures
- Specialized HW tests
- Controlled emergency switch-off

One comprehensive test for all chosen accelerator device types could include several smaller steps, specialized for every device type. For example, the commissioning HW test includes many types of devices such as pulsed power supply, ramped power supply, vacuum valve, different beam diagnostic devices, etc. As an example, pulsed power supply devices perform the following steps in the commissioning sequence:

- Switch on power
- Reset
- Check interlocks
- Read out maximum possible current and drive it
- Check target/actual current
- Read out minimum possible current and drive it
- etc...

Graphical User Interface (GUI)

The GUI library encompasses all developed sequences. Initially, users must choose the desired test procedures from the library. Subsequently, they need to select the specific hardware (HW) to be tested. Once the test types and the list of dedicated devices are chosen, the user can initiate the tests. They can then follow live in the GUI how each test step for every selected device is performed and monitor the overall test status.

Reporting

The test results are documented in a report. The sequencer generates automated reports and sends them via email to configured subscribers. The report format is customized to meet the demands of the expert group, with options such as PDF and XLS tables. Users can choose the type of content they wish to receive, selecting between failed tests only or information about all performed tests. The structure of reports for complex tasks, such as commissioning HW tests, is still under discussion.

Current Work in Progress

As electricity costs have become a significant concern in recent years, GSI has explored possibilities to reduce power consumption even during beam times. One such avenue is the activation of an energy-saving mode when the accelerator fails, and extended downtime for diagnostics and repairs is anticipated. Two main types of devices were identified, which exhibit high power consumption even in standby mode – pulsed power supply for magnets in transfer lines and ring RF. Both types will be switched off during the spare mode. The challenge with the pulsed magnets lies in their hysteresis. Recent investigations revealed that the hysteresis of magnets can be neutralized with a conditioning procedure involving several ramps up to the maximum and minimum currents. Additionally, it was decided to perform the conditioning procedure with the sequencer every time before beam setup. Based on the experience shared by FRS colleagues, this approach is expected to enhance the setup robustness.

Outlook for 2024

There are plans to systematically incorporate additional device types into the sequencer. New FESA models, developed by external suppliers, will be delivered with pre-included sequences. The GSI commissioning periods will serve to establish the tool as a standard for the operator team and expert groups.

9.21 Preparatory activities for FAIR commissioning

Authors: Stephan Reimann, Vesovolod Kamerdzhiev, Yuri Valdau, Kirill Grigoryev, Oksana Geithner

Activities in preparation for FAIR commissioning continued over the course of 2023. As part of the re-baselining process, an integrated commissioning schedule was generated, which outlines the commissioning process for the defined early-science and first-science intermediate goals and already contains a large number of important milestones that are essential for the start of commissioning activities in the accelerator tunnels. As part of the project re-baselining, the focus of the entire FAIR project was also aligned with the new interim goals (early science, first science and first science+) which is reflected in the commissioning preparation activities as well. For example, the commissioning workshops at SFRS were intensified accordingly.

Planning Status

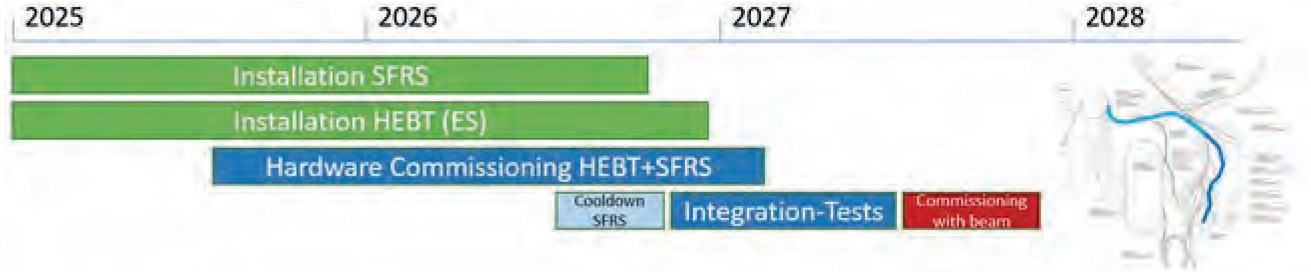


Figure 104. Commissioning frame schedule for early science scenario after re-baselining.

According to current planning, the first interim goal of FAIR Early-Science should be achieved in December 2027. This includes hardware commissioning in accelerator and supply tunnels as well as initial commissioning with beam, so that the new beamline and part of the Super-FRS can be used for user operation with the defined project completion parameters (PCP) from this date. In addition to the injectors of the existing GSI system (UNILAC-SIS18), FAIR Early-Science includes the beam line from SIS18 to the Super-FRS, consisting of the beam sections of the HEBT (T1S1, T1S2, TSX1, TSF1) and the sections of the Super-FRS (T1F2, TFF1, FMF1, FMF2, FMF3 and FHF) up to the High Energy Cave (Figure 104).

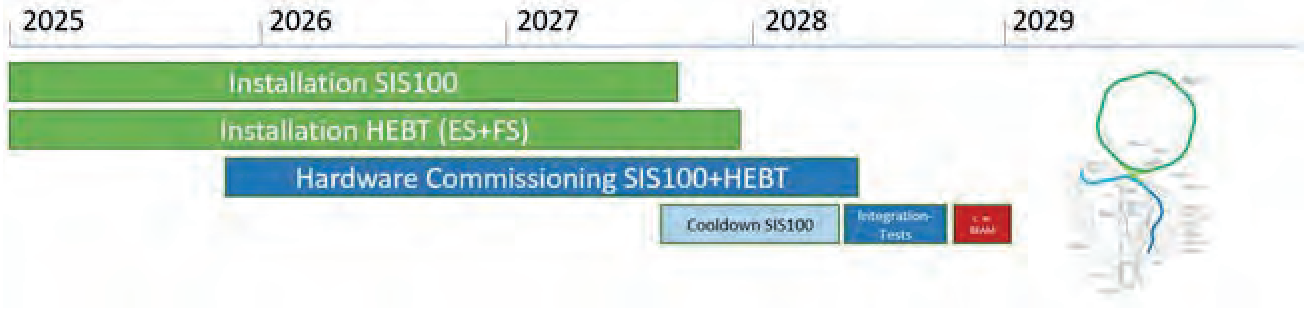
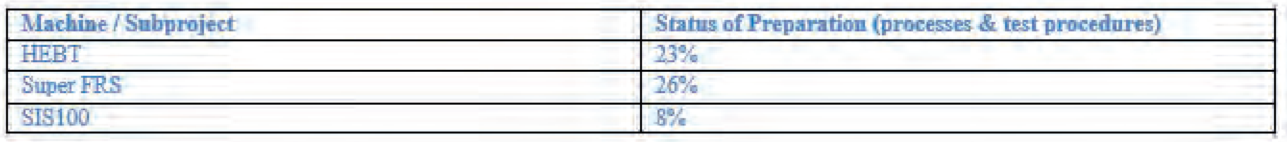


Figure 105. Commissioning frame schedule for first science scenario after re-baselining.

Commissioning of First-Science was also planned in the same way. First commissioning activities in the supply tunnels will therefore be possible as early as the end of 2025. The cooldown of the SIS100 will take place at the end of 2027 and beam commissioning is planned for one year later, so that a first experiment can be supplied from the end of 2028. However, only a simplified SIS100 cycle will initially be developed for the first experiment. Complex cycles, parallel operation and fast ramps will only be successively put into operation and handed over to user operation in the following years.

In order to refine the planning and identify further dependencies, the commissioning workshops for the system types were continued after re-baselining. In this context, the planning for cryo-commissioning and for the Personal Access System (PAS) were also implemented, as these have been emphasized as major prerequisites for the later phases of the commissioning process. At the same time, the implementation of automated tests has progressed.

These have also already found their way into the standard re-commissioning processes of the GSI existing accelerators. The current overall status of preparations is shown in table (Figure 106).



Machine / Subproject	Status of Preparation (processes & test procedures)
HEBT	23%
Super FRS	26%
SIS100	8%

Figure 106. **Table to progress of the commissioning preparation in terms of commissioning workshops and test automation.**

9.22 Development of a combined electric and magnetic field deflector element for the JEDI experiment

Authors: Kirill Grigoryev, Yury Valdau, Maurizio Fabian Schubert

A search for a permanent Electric Dipole Moments (EDM) of fundamental particles like protons or deuterons is one of the main goals of the JEDI collaboration. Precursor experiment at the Cooler Synchrotron COSY at Forschungszentrum Jülich have led to the design of a new ring concept. It requires development of a bending elements incorporating both magnetic and electric fields. Constructing of a high-stability electric and magnetic field deflector is a key technical challenge for this project. The aim was to reach 7 MV/m with 60 mm spacing between electrodes in the presence of a magnetic field.

The experimental setup

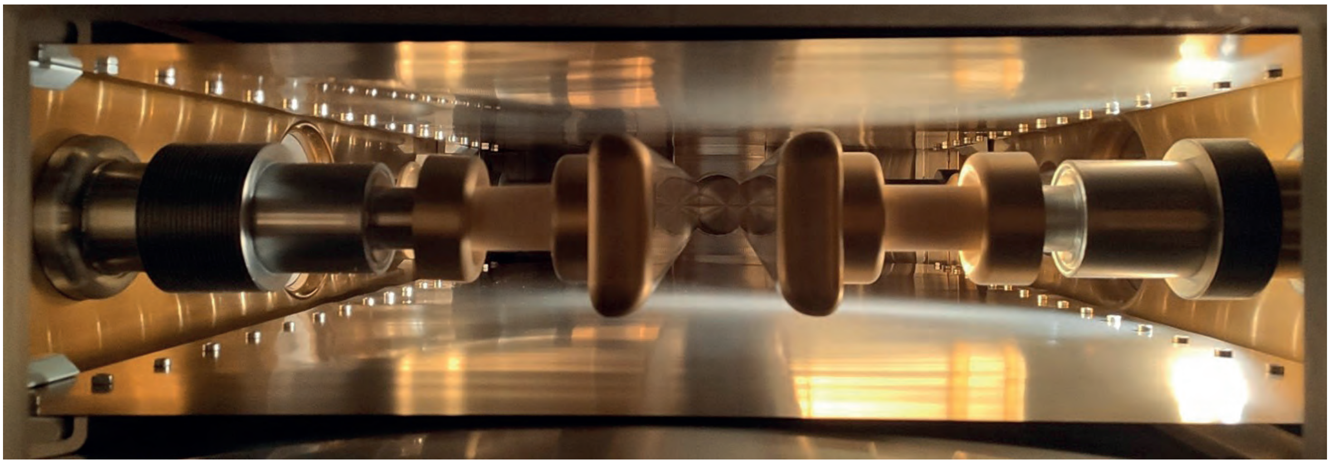


Figure 107. The deflector electrodes on ceramic insulators inside the vacuum chamber.

The experimental setup utilized a large-gap dipole magnet with a 1.4 m large vacuum chamber, which was suitable for testing a 1080 cm long deflector prototype. Two polished Rogowski-shaped aluminum electrodes coated with TiN were mounted on ceramic insulators inside the vacuum chamber. Thin titanium foils were positioned above and below the electrodes to maintain a constant distance from the grounded surface. High-voltage feedthroughs attached to the center of each electrode were connected to individual precise 200 kV high-voltage bipolar power converters. The setup included turbo-molecular, cryo, and ion-getter pumps to keep the vacuum inside the chamber at approximately 10^{-9} mbar during the tests.

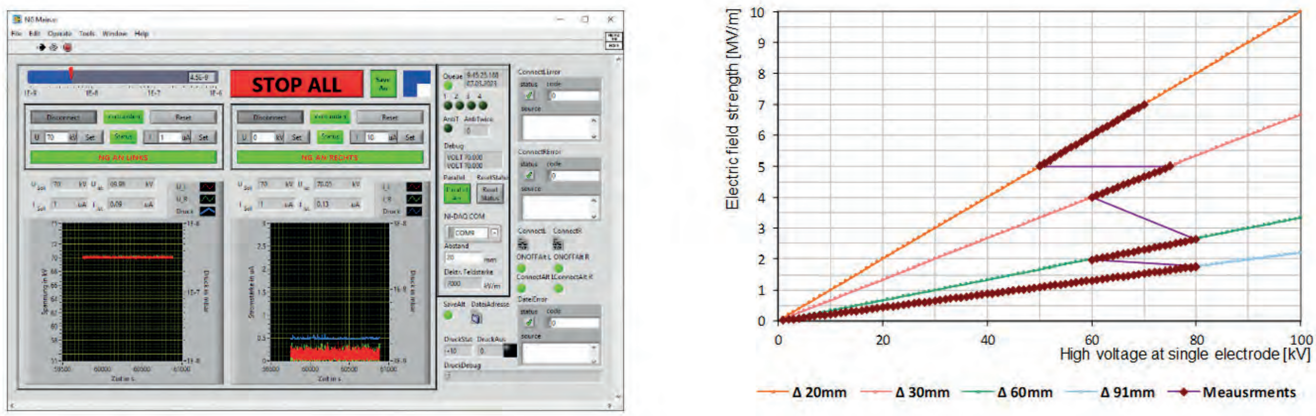


Figure 108. The program to operate the high-voltage converters, control vacuum and local area interlock status (left). The step-wise measurement results (thick lines) and expectation (thin lines) on the right side.

Due to the potential production of X-Rays during the high-voltage breakdown when applied voltages between the electrodes exceeding 30 kV, access to the experimental setup was restricted. Thus, all operations were conducted using a specially designed remote control system (screenshot on the left side of Figure 108), that was integrated into the personal safety interlock system of the accelerator facility.

The measurements

During initial conditioning attempts, the electrodes were conducted without a magnetic field being present. The distance between the electrodes was set to a maximum value of 91 mm upon installation into the vacuum chamber. A field strength of 1.75 MV/m was achieved at 80 kV (as indicated by measurements along the blue curve in IMG2) with a dark current below 100 nA. Subsequent measurements were performed with a minimum necessary magnetic field of 150 mT. Due to time constraints the high-voltage measurements were conducted with interrupts for access to the accelerator facility. Further measurements at a nominal distance between the electrodes showed instabilities at higher electric fields. However, during available time for the deflector experiments, the desired electric field strength of 7 MV/m required for the prototype tests was successfully reached.

Selected publications of 2023

- [1] Grigoryev, K. ; R. Gebel, R. ; Schubert, M. ; Valdau, Yu. ; et al.: Development of a combined element with an electric and magnetic fields for the JEDI experiment, in Proc. IPAC'23, Venice, Italy, May 2023, pp. 4406-4408. doi:10.18429/JACoW-IPAC2023-THPA189

9.23 Production of the HESR Injection Kicker System

Author: Yury Valdau

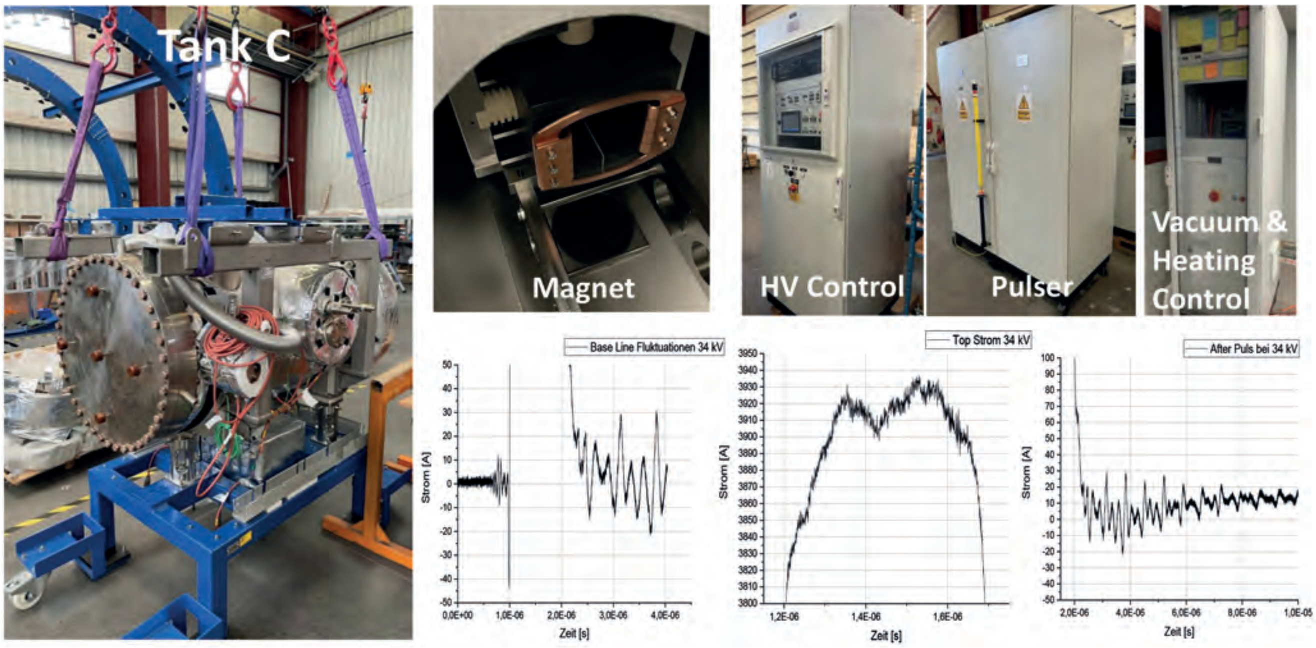


Figure 109. Tank C, magnet, HV control and pulser, together with vacuum and heating control system during the FAT. Puls parameters measurements for the antiproton injection in the HESR during the FAT.

The Forschungszentrum Jülich (FZJ) together with international partners is responsible for the design and construction of the High Energy Storage Ring (HESR) for the Facility for the Antiproton and Ion Research (FAIR) in Darmstadt. The HESR injection system has been fully designed, produced and delivered to the FAIR storage area in Weiterstadt in 2023. The system has been built by a collaboration of GSI, FZJ and the SigmaPHI company and reach a HESR injection system design parameters. The key part of the HESR injection system is an injection kicker system, built in a close collaboration of the authors of Ref. [1-3], discussed in this report.

The HESR injection kicker system consists of four pulsed magnets, located in two vacuum tanks (A and B), high voltage cables, and one HV control and pulser system per magnet [1]. In addition to the HESR injection kicker system, a separate test system (HV control, pulser, cables, and magnet in a separate vacuum tank C) has been built for the system development, performance studies and can be used as a source of spare parts. Each vacuum tank with kicker magnets and pulsers have been a subject of a separate Factory Acceptance Test (FAT) process and delivered separately. The side acceptance test (SAT) has been done simultaneously with FAT by GSI and FZJ employee at SigmaPHI due to the space limitations at the GSI campus.

The kicker vacuum system is designed according to the FAIR standards [2]. Each vacuum tank can be bake-out using common for the complete kicker system heating and vacuum control system and is ultra high vacuum compatible. Vacuum properties of individual kicker tanks have been tested separately during the FAT. Results of the rest gas analysis and helium leak measurements are part of the FAT documentation provided by the SigmaPHI. The pulsed magnets are fixed on their positions in the tanks on the rail system. The positions of the magnets are measured and known to the high precision.

The kicker system is designed to provide the last 6.4 mrad kick to the in the HESR injected beam of antiprotons or positively charged ions and can operate at maximal repetition rate of 0.1 Hz. The kicker magnet puls parameters are specified for generation of injection pulse every 10 seconds, with pulse raise and fall times of 220 ns, respectively, and a 500 ns flat top time [3]. Pulse amplitude fluctuations at the flat top and after the puls are kept smaller than 1% of the total pulse amplitude. This should allow accumulation of up to the one thousand injection pulses in the HESR storage ring parallel to the cooling and bunching processes.

Each magnet is connected with individual pulser by a six HV coaxial cables in a so-called Blumlein topology. The pulser is build using IGBT semiconductors and allow fast polarity interchange (~30 minutes) without access to the kicker tank in the accelerator tunnel. Matching of the pulser to the magnet is done using proper choice of the cable length and adjustable capacitance on both sides of the HV coaxial cable. All five pulsers have reached the design pulse parameters and can be used at the HESR. Each HV control system contains power supply and specially designed control and interlock system. In Figure 109 the photos and pulse measurements done during the FAT of Tank C in SigmaPHI are presented.

The HESR injection kicker system, produced by the FZJ and SigmaPHI fully meets the design parameters. All the design and FAT documentation are available and stored in the EDMS system. Complete HESR injection system is ready for the installation and is stored in the FAIR storage hall in the Weiterstadt.

References:

- [1] R. Tölle et al., “Injection Kicker for HESR at FAIR using Semi-Conductor Switches”, in: Proc. 6th Int. Particle Accelerator Conf. (IPAC'15), Richmond, VA, USA, May 2015, pp. 3770-3772, DOI:10.18429/JACoW-IPAC2015-THPF034
- [2] F. Zahariev et al., “Developments for the Injection Kicker Vacuum System of the HESR at FAIR”, in: Proc. 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper WEPVA050, pp. 3369-3371, ISBN: 978-3-95450-182-3, https://doi.org/10.18429/JACoW-IPAC2017-WEPVA050, http://jacow.org/ipac2017/papers/wepva050.pdf, 2017.
- [3] Yu. Valdau et al., "Design and production of the fast HESR-injection kicker magnets", in: Proc. IPAC'23, Venice, Italy, May 2023, pp. 4363-4365. DOI:10.18429/JACoW-IPAC2023-THPA167

9.24 Activities of Operation Infrastructure Support

Author: Gertrud Walter

In 2023 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 with the accelerator and experiment departments. Special examples of these ongoing activities are the construction of different parts and devices for the FAIR accelerators including the Alvarez upgrade at the UNILAC. In addition, various experimental setups have been supported during FAIR phase 0 and the preparation of FAIR early science and early science+, respectively.

Department Mechanical Workshop and Metalworking

Head: Markus Romig, Authors: Markus Romig, Stephan Teich, Jens Holluba

The Department Mechanical Workshop and Metalworking continuously supports the existing FAIR accelerators as well as all experiments by manufacturing a variety of special technical devices, examples are shown below. To prepare the FAIR installation works, a first series of HEBT vacuum chambers was produced in our metal working workshop in addition to the further development and training of complicated welding procedures to support the cold mass installation of the superconducting SIS100 magnets and the related string tests.

Department Technology Laboratory

Head: Tanja Dettinger, Authors: Tanja Dettinger, Mathias Henke

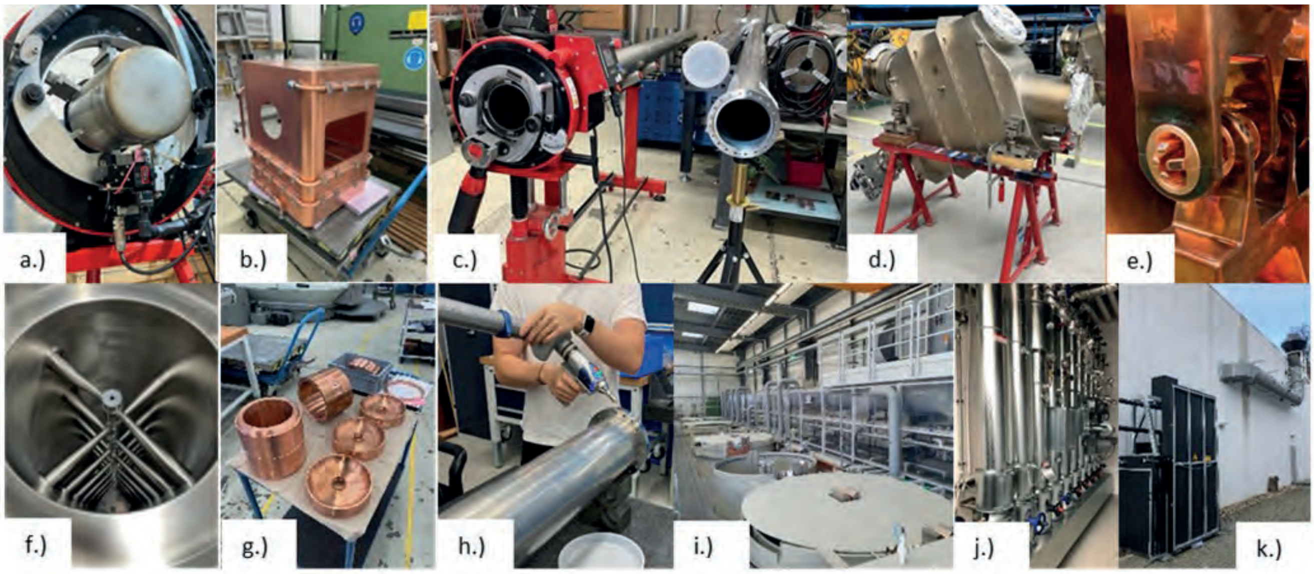


Figure 110. a.) FAIR current comparator's thermal shield cold supply, b.) welded Alvarez 2.0 tuner, c.) welding device for the HEBT beam transport vacuum chambers, d.) one of the ESR electron cooling chambers surveyed to generate a 3D model, e.) superlens electrodes that have been replaced during the shutdown works, f.) demo structure of p-Linac, g.) sparse drift tubes for Unilac, h.) 3D precision scan, i-k.) refurbished Galvanic workshop, i.e. i.) bath vessels, j.) technical supply units, and k.) waste-water station and exhaust air outside the building.

The Department Technology Laboratory supports in-house manufacturing processes especially for soldering or heat treatment, using our vacuum oven, including advanced R&D procedures. Another focus is on our 3D precision measurement device to perform quality assurance of in-house manufactured components often in combination with leak testing. This measurement device is also used for 3D surveys and reconstruction of drawings in case of older equipment already in use but with poor documentation status. Furthermore, in 2023 the Galvanic workshop refurbishment has continued to guarantee the high-gloss Cu plating of the large-scale series tanks for the Unilac Poststripper Upgrade Alvarez 2.0. The Galvanic facility is unique worldwide with respect to the large size of components to be Cu-plated.

Besides the refurbishment of the Galvanic Workshop, which will be finalized with commissioning in 2024, several projects/activities have been carried out by the departments of OIS. Examples are shown in the following figures in Figure 110.

10. Research in accelerators, detectors, electronics and IT

10.1 Activities of the Department Experiment Electronics

Head: Thomas Bretz
Authors: Jörn Adamczewski-Musch, Holger Brand, Thomas Bretz, Holger Flemming, Karsten Koch, Nikolaus Kurz, Michael Traxler, Michael Wiebusch

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 for the production of larger quantities. With the Multi Branch System (MBS) and the Data Acquisition Backbone Core (DABC) two data acquisition solutions are actively developed and supported, which complement the offered data acquisition hardware. For data analysis, the GO4 system meets the needs of the ever-increasing requirements for experimental setups towards FAIR. An essential backbone for the success of any experiment is a robust and reliable control system. Various such control systems, mostly based on LabVIEW, EPICS, C++ and Python, are offered. In addition to common large-scale systems, Experiment Electronics provides support and solutions for everyday challenges in facilities and laboratory setups.

Open Door Day

A special event in 2023, was the participation in the Open Door Day, for which dedicated live experiments had been developed and presented. Two turning knobs allowed to adjust the frequency of the wobbling of a mirror in x- and y-direction. Deflecting a laser beam on the mirror allowed displaying simple (circle) to complicated Lissajous curves on a screen demonstrating the concept of the superposition of two perpendicular oscillations. With a small discrete circuitry, developed originally in the scope of a student internship, we demonstrated how a simple modulation of a laser beam can be used to transfer songs from Led Zeppelin and others in high quality over large distances to a receiver applying concepts also used in our daily electronics development. Also built in the context of a student internship, a infinite pendulum driven by a simple microcontroller demonstrated the application of an electric coil acting as detector and concurrently as driving force of the pendulum. One of our Time-To-Digital Convertes was utilized demonstrating the measurement of millimeter travel distances for signals at the speed of light by measuring the round-trip time on conductors with adjustable lengths.

Design and Production

One of the highlights of the electronics department at GSI is our own assembly facility for printed circuit boards (PCB). Electronics circuits developed for cutting edge experiments, have to be disentangled and printed circuit boards designed before production. After manufacturing of the printed circuit boards themselves at external companies, our professional production chain is utilized to manufacture the end product. During 2023, almost 90 different printed circuit boards have been designed by our layout team. A similar number of projects have been manufactured in our facilities of which 85% were projects primarily developed by our development team and about 15% were designs contributed by other departments. Ranging from simple plug-adapters to high-density cutting-edge 16+layer PCBs, around 8500 printed circuit boards were assembled with a total of almost 4 Mio. electronics components at average material costs of 6500 Euro per project or 55 Euro per board. A significant fraction of the 2023 production was the assembly of 1100 DiRICH5 boards for the CBM-RICH, one of the FAIR detectors.

An important milestone in the production process was reached during 2023 by our excellent production team: For the first time, they were able to assemble electronics components with a size specification 0402 metric (01005 imperial, 400 µm x 200 µm) allowing for higher integration density in future projects, an important benchmark for today's cutting edge electronics as required for the FAIR experiments.

A New Custom Discrete Amplifier-Shaper-Discriminator

In the context of the R^{3}B experiment, a discrete Amplifier-Shaper-Discriminator circuit was developed and successfully implemented. This pragmatic design replaces a classic integrated circuit (ASD8 analog read-out ASIC), which is no longer available due to its outdated manufacturing process.

The drift chambers used in the experiment play a crucial role in particle tracking, momentum measurements and particle identification. As any detector, they require specialized front-end electronics to achieve the desired sensitivity and accuracy in terms of leading edge time (drift time) and pulse charge (particle energy loss). The designed circuitry uses discrete miniature SMD components and the LVDS inputs of a low-cost FPGA to achieve a performance similar to the previous solution at comparable power consumption. Its high integration density allows the implementation of sixteen amplifier channels onto a single credit card-sized board which connects directly to the chamber.

With this circuit, a customizable solution with excellent performance is available.

[*] Michael Wiebusch, Henning Heggen, Michael Heil, A custom discrete amplifier-shaper-discriminator circuit for the drift chambers of the R3B experiment at GSI, JINST 19 (2024) C01044, DOI:10.1088/1748-0221/19/01/C01044

News from Selected other Projects

- For the first time, a successful radiography was carried out with ions by flight-time measurement during a beam time at MedAustron in the context of a Schrödingerstipendium (F. Ulrich-Pur, SAP: 65302) uitilizing our DiRICH5di readout electronics. The implemented time-to-digital conversion is based on a Field Programmable Gate Array (FPGA) with customized firmware developed in our department. [*] F. Ulrich-Pur, et al., First experimental time-of-flight-based proton radiography using low gain avalanche diodes, Physics in Medicine and Biology (in print), DOI:10.48550/arXiv.2312.15027
- A new generation of 128 channel amplifier / sampling TDC readout boards (MMPC_ROB3) for the readout of SiPMs successfully stood the beam test at R3B and SFSRS under vaccum.
- The speed of the front-end electronics for CBM has been increased.
- Due to the change of licence policy and its decreasing quality, GSI has decided to stop the yearly purchase of National Instrument's LabVIEW™ (~90.000 €/year). As GSI owns enough valid unlimited licenses, all running system can further be operated and maintained. For future projects, our departments has worked on a migrations path utilizing open source software. A first project for bakeout of parts of the accelerator was successfully deployed.
- As a replacement for National Instrument's RIO/FPGA hardware, the MUPPET1 module, an arbitrary multi-channel pulse pattern generator including a time-to-digital converter with a custom open source Python frontend has been developed. In 2023, it was successfully deployed to several other groups working at GSI and FAIR experiment.

Application Specific Circuits

Whenever extremly high intgeration density or a large number of channels have to be served by readout-electronics at acceptable costs, Application Specific Integrated Circuits (ASIC) are an ideal choice. Having an in-house design team for this highly challenging design task is a clear locational advantage of GSI for FAIR.

During 2023, the CTR16 a state-of-the-art transient recorder, were successfully put into operation, certainly the most complex ASIC so far designed in our design team. During summer, an unexpected option for the production of an upgraded design opened up which allowed to submission of a second iteration resolving a few minor bugs facilitating a more stable operation. Production and testing of the same is expected for the first half of 2024.

Besides the application of previous developments (QFW) for the readout of profile grids of the beams diagnostics, also a charge sensitive preamplifier (AWAGS) has been started to be utilized and tested at various places.

Towards the implementation of the TSMC 65nm process – the most widely used technolgy in our business – first circuit simulations have been utilized and first layouts drafted. With the submission of first real test structures for production reaching another important milestone is expected for 2024.

New Release of the Multi-Branch System (MBS) V7.0

With Version 7.0, the GSI data acquisition framework now supports a number of new platforms, e.g. Debian 11 for PCIe readout, and the IFC PPC linux for VMEbus. Additionally, the mesytec MVLC controller has been integrated. This FPGA-based controller allows fast low-latency readout of VME modules via super speed USB3 connections to any host PC. To utilize this hardware in the scope of multiple branch data acquisition, several software components have been adopted and developed for the host PC: a special MBS readout process, the TRIVA trigger module control, and new commands to access VME registers via USB.

For all new platforms the FAIR white-rabbit timing receivers VETAR and PEXARIA are supported to mark each event with a global time stamp, allowing synchronization of hybrid or streaming readout systems.

The new FAIR mass storage interface FSQ has been included to MBS V7.0. Acquired listmode data can be directly written from MBS to the FSQ storage servers of the FAIR IT centre. This features the file transfer both to the lustre file system of the "green cube" compute nodes and to the long term TSM tape archive.

10.2 Activities at the Department Detector Laboratory

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

DTL engaged even stronger in serial production of instrumentation for the FAIR facility. As such, serial production of the Particle Detection Combination devices for the high energy beam monitoring at FAIR has started. This is an important in-kind contribution of GSI. Two first devices were successfully assembled and tested. 15 further instruments will follow immediately. A total of 45 devices are projected for the FAIR facility.

Similarly, the final first-of-series of the large-volume multi-channel ionization chamber MUSIC for SFRS was built and tested successfully in a heavy-ion beam time. A second even larger version will be set up in 2024.

To aid these activities, a new read-out chain based on the highly integrated electrometer chip TERA09 was built, tested and finalized successfully. It will also be used to modernize the irradiation control in the medical facility cave M.

The CBM Silicon Tracking Station STS has been brought to the start of serial production. 26 first of series detector modules out of 876 were assembled. They will feed to the assembly of the three first of series detector ladders, the next integration stage in the assembly of the STS. In parallel a first prototype full ladder was assembled from 10 pre-series detector modules. Serial production will be realized at GSI and KIT.

Two tracking systems based on large-area Si micro strip detectors are constructed for the R3B and SFRS EC setups. The detectors were commissioned at COSY, FZ-Jülich with deuteron- and proton-beams.

The large high pressure chamber (20 bar) for an active target setup was tendered and produced. It will be employed first for the AMBER detector system and later for R^{3}B at FAIR.

DTS engaged in assembly and testing of ALPIDE CMOS MAPS sensors on low material flexible carrier PCBs. Full readout of multiple assemblies was proved using proton beam at COSY, FZ-Jülich.

After the successful demonstrator project PFAD, the complex, cylindrical dual layer, double sided silicon proton tracker STRASSE has gone into its development and prototyping phase. DTL cooperates here together with LTU in Ukraine in the field of micro assembly and integration on a project driven by TU Darmstadt for experiments at RIKEN. The full data chain from readout ASIC STS-XYTER to PCIe-Interface card GERI, that was originally developed around the CBM-STS project for the cooperation with JINR, is employed for this experiment. The readout chain similarly is being used for STS quality control measures and tests as well as the CBM-STS cooperation with E16 at JPARC.

For the use of particle tracking through the future Super-FRS facility a prototype of a scintillating fiber based tracker was developed, built and tested. This technology will also be employed in several NUSTAR experiments. The readout is realized through SiPMs and the GSI-developed PADIWA electronics.

Following successful proof-of-principle studies with small-area LGAD strip sensors, where DTL realized the integration, a design concept for a large-area low-mass LGAD system for precise time-measurements has been developed, with applications ranging from nuclear to medical physics. The intended system will consist of trench-isolated (TI-)LGAD strip sensors connected through low-mass aluminum flex cables to FPGA-based TDCs developed at GSI.

Towards the development of a CMOS pixel sensor for the CBM micro vertex detector the sensor prototype MIMOSIS-2 was designed and produced for evaluation, an activity lead by IPHC, Strasbourg. DTL was engaged in a series of beam tests that helped to shape MIMOSIS-II.

10.3 Research of the IT Department

Head: Dr. Thorsten Kollegger (GSI)
Author: Mohammad Al-Turany

In the ever-evolving landscape of scientific computing and data management, the IT department has undertaken remarkable strides in multiple domains throughout the preceding year. This report serves to illuminate the noteworthy accomplishments and progressions achieved by distinct groups within the department. As the cornerstone of the infrastructure essential for realizing the GSI/FAIR mission, the IT Department remains dedicated to cultivating unparalleled expertise in technical analysis, design, implementation, operation, and support of computing infrastructure and services.

Highlights in 2023

Software development

Advancements in the data transport framework (FairMQ):

Several enhancements have been made to the FairMQ framework, including consistent transport interruption and resumption, improved control mechanisms, and tunable size of metadata for optimized socket configuration. These advancements further solidify FairMQ's position as a reliable and efficient tool for data communication and processing in distributed systems.

Deployment of FairMQ Devices with DDS:

The dynamic deployment system (DDS) has been successfully utilized for the deployment of FairMQ devices on Event Processing Nodes (EPN) of ALICE. This deployment manages an impressive 130,000 devices per session across several hundred nodes, with each node handling approximately 400 devices. The communication between these devices is facilitated through shared memory, ensuring efficient data exchange and processing. The system was successfully used during the beamtime at CERN.

The Online device controller (ODC):

The ODC framework has seen significant enhancements in asynchronous task handling, dynamic resource extraction, and improved failure handling. These improvements contribute to smoother operation and more robust performance of data communication processes, particularly in environments with high data throughput and complex configurations. The system was under heavy use in the heavy ion run of ALICE experiment at CERN

Expansion of SIMD Implementation:

The IT department continues to lead in the development and promotion of Single Instruction, Multiple Data (SIMD) implementations for improved computational performance. The SIMD implementation, integrated into the GCC compiler, has reached its 13th release, showcasing ongoing refinement and optimization efforts. Dr. Matthias Kretz's contributions to SIMD programming have been recognized through invitations to conferences and collaborations with industry partners.

C++ Standardization Efforts:

The IT department remains actively involved in C++ standardization efforts, particularly in the integration of SIMD types into the upcoming C++26 standard. Collaborations with Intel and engagements at prominent events such as CppCon '23 and the CppCast podcast have further elevated the visibility and impact of GSI Darmstadt's contributions to the C++ community.

Storage systems

Conversion of TSM Servers under LTSM to RedHat Servers:

One of the major initiatives undertaken by the storage group in the IT, was the conversion of the LTSM servers to RedHat servers equipped with TSM cluster software. This transition aimed to enhance the efficiency and reliability of data storage and retrieval processes within the GSI, paving the way for more streamlined operations and improved data management capabilities.

Outlook for 2024

Building upon the significant advancements made in the realm of scientific computing and data management this year, the IT Department is poised to embark on a trajectory of continued innovation and progress. Looking ahead, several key initiatives and areas of focus are anticipated to shape the landscape of IT infrastructure and services at GSI/FAIR: Future endeavors will concentrate on scaling the deployment methodology to accommodate evolving computational requirements by online processing of the GSI/FAIR experiments. Significant updates and expansions are planned for the HPC cluster and storage systems to cater to the escalating requirements of the experiment.

Selected publications of 2023

- [1] Vuillaume T, Al-Turany M, Füßling M et al. The ESCAPE Open-source Software and Service Repository [version 2; Open Res Europe (2023 DOI: 10.12688/openreseurope.15692.2
- [2] P1928R2 Merge data-parallel types from the Parallelism TS 2 Matthias Kretz 2023-01-15
- [3] P2772R0 std::integral_constant literals do not suffice - constexpr_t? Matthias Kretz 2023-01-17
- [4] P1928R4 std::simd - Merge data-parallel types from the Parallelism TS 2 Matthias Kretz 2023-05-19
- [5] P2781R1 std::constexpr_v Zach Laine, Matthias Kretz 2023-05-04 2023-05
- [6] P2876R0 Proposal to extend std::simd with more constructors and accessors Daniel Towner, Matthias Kretz 2023-05-18
- [7] P1928R6 std::simd - Merge data-parallel types from the Parallelism TS 2 Matthias Kretz 2023-06-19
- [8] P2781R3 std::constexpr_v Zach Laine, Matthias Kretz 2023-06-12
- [9] P3024R0 Interface Directions for std::simd David Sankel, Jeff Garland, Matthias Kretz, Ruslan Arutyunyan 2023-11-30

10.4 Activities in technology transfer at GSI and FAIR

Head: Dr. Tobias Engert
Authors: Tobias Engert, Alicija Surowiec, Yvonne Leifels

The Technology Transfer Department (TTR) is a staff unit that reports directly to the Administrative Management. With 11 FTEs, including 8 FTEs from third-party funds, the TTR is responsible for handling services and contract research, innovation management, business development and technology marketing.

Transfer strategy

The transfer strategy with defined goals and measures was adopted by the GSI Supervisory Board in 2021. Since then, TTR has been pursuing the measures of this strategy in a five-year plan. The central task of this strategy is to increase the social benefit of scientific results and technologies. The measures focus on the technical utilization and commercial exploitation of scientific results from research and technological developments from the operation of the facilities.

GSI pursues three main goals in the transfer mission:

1. creating a culture of innovation by promoting an awareness and understanding of transfer options.
2. optimization and strengthening of transfer activities, creation of an effective transfer structure using adequate resources.
3. developing an indicator system and monitoring transfer activities to analyze the impact of transfer instruments.

Highlights in 2023

Digital Open Lab

The GSI/FAIR Digital Open Lab (DOL) was established on the 4th floor of the Green IT Cube, which was equipped with technical infrastructure during 2022 financed by EU-EFRE funds from the state of Hessen. The DOL is a real-world IT laboratory and is intended to provide research and industry partners - especially AI start-ups - with a platform to test and develop technologies of the future. The DOL was officially opened in March 2023 with the cooperation with the Hessian Center for Artificial Intelligence "hessian.AI". Since then, the AI innovation lab, which is unique in Germany, has been part of the GSI/FAIR Digital Open Lab with its AI computing infrastructure. The Digital Open Lab thus forms the basis of the Hessian AI transfer ecosystem and serves as a contact point for over 70 companies, start-ups and scientists with the central aim of providing access to an AI supercomputer infrastructure. AI systems and applications can be developed, trained, tested and evaluated in the AI lab.

In 2023, GSI and FAIR were partners of the first hessian.AI conference "The hessian AICon": The three-day conference took place at the Science and Congress Center Darmstadtium in Darmstadt. Participantds received comprehensive information on the latest AI research trends. There were networking opportunities, a start-up exhibition and the chance to gain deeper insights into hessian.AI and the AI ecosystem.

As partners of "The hessian AICon", GSI and FAIR underlined their commitment to AI application in various fields. The opportunities in the Green IT cube within DOL were presented to private and public partners within the Digital OPEN Lab: provision of infrastructure and IT competencies for joint development projects and jointly operated high-performance computing systems. In addition, the Accelerator Physics department offered insights into practical applications of AI in the development and operation of large accelerator facilities

.In collaboration with GSI/FAIR and the Technical University of Darmstadt, the European Space Operations Center (ESOC) hosted the Artificial Intelligence Symposium on Technology, Applications, and Research (AISTAR) for a second time in 2023. The symposium created a space for connections, networking and the exchange of ideas and facilitated new contacts and collaborations within the AI community.

DOI:10.15120/GSI-2024-00500

Further cooperation in the Digital Open Lab

The Digital Open Lab will serve as a platform for the CISPA Helmholtz Center for Information Security for the further development of IT security-relevant applications, processes and infrastructures. Full hardware integration into DOL is scheduled for completion in Q1 2024.

DC Smarter is another example of start-up support. The German IT start-up was the first industrial partner to move into DOL where it is making its DC Vision® solution available. Through a combination of digital twin and augmented reality, the software optimizes central tasks in a data center such as remote hands services, documentation management and visual inspections. In the Green IT Cube, the functions of the DC-Vision solution can be tested in real operation and - according to the aim of the cooperation - provide impetus to further expand the software. At the same time, the IT experts at the high-performance data center are provided with state-of-the-art technology for the operation of a sustainable data center

A cooperation agreement was also concluded with NDC Data Center GmbH. NDC is part of the GARBE real estate developer group and serves as a transfer partner for future developments of cube technologies. The subject of this new cooperation agreement is the use, further development and marketing of the Cube concept, in particular the energy-efficient cooling system. In return, GSI received the full IP rights to use the entire Cube concept.

Day of the Open Data Centers

“Where does the internet actually live” was the motto of the Open Data Center Day on September 29th, 2023. Twenty compute centers throughout Germany invited interested persons to visit modern data centers. At GSI the cooperation partners in the DOL, DC Smarter and NDC-Garbe participated in this event. The Director of NDC Garbe, Peter Pohlschröder answered questions and presented the activities in the DOL to visitors

Entrepreneurship activities in 2023 – Transfer Academy

GSI is participating in the Helmholtz Academy for Intrapreneurship (HAFIS) with its partners at KIT, FZJ and HZDR. The Helmholtz Academy for Intrapreneurship (HAFIS) strengthens entrepreneurial thinking and action among researchers. The aim is to enable researchers to identify, design and prototype innovative transfer projects. Project-based learning approaches from companies and university education are successfully used and transferred to the target group of researchers. In this way, around 25 GSI researchers will be empowered over the three-year project period and around 6 transfer projects will be initiated in parallel. At the end of the funding period, further Helmholtz Centers are to be successively integrated into the Academy

HEPTrepeneurs

In addition, regular in-house training courses in the field of entrepreneurship are offered. In online webinars, speakers present their start-up successes, impart crucial skills in the field of entrepreneurship or provide information on the pitfalls of spin-offs. With a three-day training school, a series of physical events was also held for the first time in 2023 to further strengthen entrepreneurial thinking at GSI. The workshops focused on promoting entrepreneurial skills in the field of high-energy physics. The lectures and interactive workshops were led by two renowned experts.

Start-up support in technology and physics

GSI and FAIR presented themselves with a stand at the Start-up & Innovation Day 2023, organized by the Technical University of Darmstadt in cooperation with the Innovation and Start-up Center HIGHEST. Over 1,700 visitors from the fields of science, business, society and politics came to the Darmstadtium congress center. With around 100 exhibition stands, the event is increasingly establishing itself as a start-up and innovation event in the Rhine-Main-Neckar region. InnoDay23 presented almost 70 start-ups that showcased their latest innovations and business models. The event also offered a platform for encounters between technology start-ups, scientists and investors, business and politics. In addition to the exhibition stands, there were lectures and panels, a pitch corner and the HIGHEST xchange area, which offered keynote speeches and discussions on topics such as energy trends and new technologies for the climate transition. In addition, various dialog formats were available for exchange and networking in the start-up ecosystem. At their stand, GSI and FAIR illustrated how cooperation opportunities for start-ups and business models can arise from the technologies of both research institutions. A particular highlight was the accelerator model, a replica of GSI and FAIR, which gave visitors a tangible understanding of accelerator technology.

Launch of the HI-ACTS innovation platform

The HI-ACTS innovation platform is being implemented by GSI together with the project coordinator DESY, the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), the Helmholtz-Zentrum Berlin (HZB) and the Helmholtz-Zentrum Hereon. The aim is to make the Helmholtz Association's accelerator technologies available to industrial users as a cost-efficient full-service infrastructure. This means that existing research infrastructures will be easier to use for industrial issues. For example, partners can use experimental time at the accelerator, as is already the case in a collaboration between the European Space Agency ESA and the Biophysics research department for radiation hardening tests of electronics for use in space or in the production of nanostructures in materials research. A proactive innovation ecosystem is being established to network with relevant partners for the transfer.

11. Research & developments for the FAIR Project

Head: Jörg Blaurock (FAIR & GSI)
Authors: Emmanuel Rosi (FAIR & GSI)

Executive Summary

Figure 111. View on FAIR construction Site in October 2023

The year 2023 was an important year for the FAIR project. On one hand the project has made good progress in all areas. On the other hand, an important decision has been made by the FAIR Shareholders relating to the continuation of the construction. Following the Corona pandemic, the war in Ukraine and the global economic consequences of these different factors, such as higher inflation and bottlenecks in the global supply chain, the costs forecast for the realisation has been increased early 2022 and communicated to the FAIR Council. To cope with this new situation, the FAIR Shareholders have initiated a scientific review of the FAIR Project in order to define a new step-wise approach of the construction towards the full version of the facility, FAIR MSV. The experts of the commission "First Science and Staging Review of the FAIR Project" recommended in October 2022 the realisation of the scenario "First Science +", i.e. including the CBM experiment.

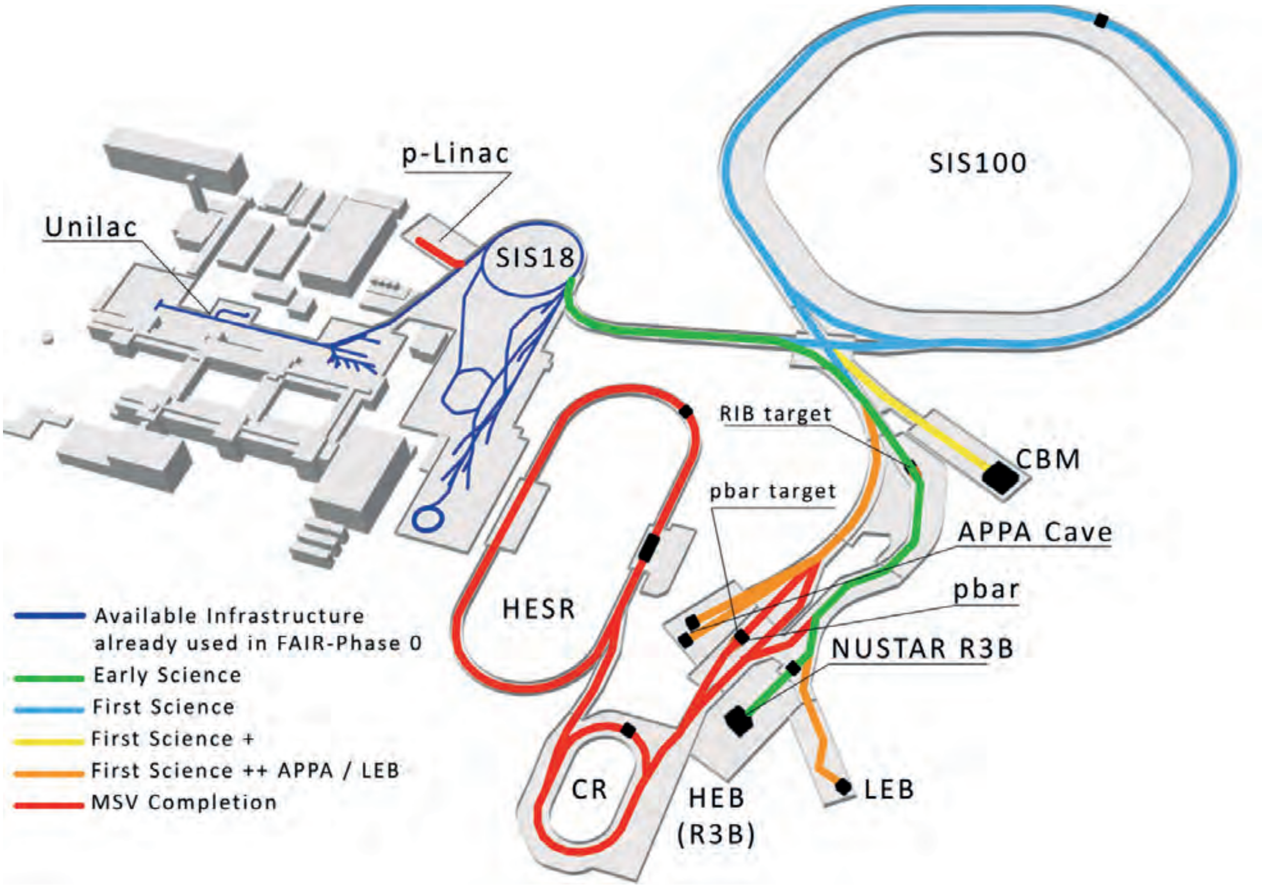


Figure 112. Constructing phases of the FAIR accelerator complex.

Nevertheless, for budgetary reasons, the FAIR shareholders have eventually decided in March 2023 to realise the scenario “First Science” and several Shareholders have granted FAIR with the corresponding budget, thus enabling the continuation of the project.

Figure 113. First 2 air coolers were installed on the building H0719A

The civil works on the north part of the construction site have been completed at the end of 2023. The work has been progressing very well on the south part. The installation of the technical building infrastructure has ramped-up in 2023, aiming at the full hand-over to TBI-operation early 2026. The first sectors of the facility will be handed-over for the accelerator machine installation early 2024.

Figure 114. **Top left: Start of cable pulling in the SIS100 tunnel – Top right: Cryo Plant installation completed – Bottom: SIS100 string test**

Several major milestones have been reached in 2023 in the area of the accelerator, such as the start of the cable pulling in the SIS100 tunnel, the completion of the Cryo plant installation, the completion of the first thermal cycle of the SIS100 string and many more.

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

Head: Dr. Haik Simon

From the technological point of view, the Super-FRS can be divided in three main groups. Firstly, the target area, comprising the production target, the components downstream after it, as well the radiation shielding around this part of beam line. The construction of target area entails the realisation of remotely controlled components with reliable performances in a harsh radioactive environment. Secondly, the superconducting magnets allowing for large apertures, and the corresponding powering and cryogenics. Thirdly, the beam diagnostic systems with high rate capability; namely detectors, their gas system, and vacuum chambers at each focal plane (so called diagnostic chambers) where detectors are hosted.

Main activities of Super-FRS in 2023 can be summarized in the tendering of a large number of former Russian contributions, intensive follow-up of running manufacturing of main components, as well as the preparation of tunnel installation which will start in the year 2024.

Target area

The radiation-resistant normal-conducting (nc) dipoles are key components in target area. Two out of three dipoles, originally in production in Russia, had to be procured again (the third dipole is already on site). At the beginning of 2023, the technical specifications were released after an extensive revision in order to adapt them to industrial manufacturing. Subsequently, the tender process could start, and finally French company Sigma Phi was awarded for manufacturing. In October, the Conceptual Design Review (CDR) was approved, and the procurement of material started. To withstand the high radiation dose, dipoles are constructed with special mineral insulated cables, which only one manufacturer (nVent Thermal, Canada) could produce in the required lengths. The contract with nVent was done promptly in 2022; in 2023, cables were produced again, delivered, tested, stored, and are now ready to be delivered to Sigma Phi.

Also the vacuum chambers inside the dipoles are technically challenging due to the high radiation, high energy deposition of remaining primary beam and high stresses in case of the use of pulsed beams. The technical specifications were re-written and adapted for industrial tender; finally, in January 2023 they were released, the tender process took place and finally manufacturing was awarded to CNIM Systèmes Industriels (CSI), France, in November 2023.

In addition to 3 nc dipoles, 3 quadrupoles and 2 sextupoles will be placed in target area. The production of nc multipoles was awarded to Buckley Systems, New Zealand. In 2023, the work was focussed on completing the design; the FDR of one sextupoles is completed and the manufacturing has started.

The 8 nc magnets require high power supply. The corresponding power converters, originally Indian in-kind contribution, were tendered by FAIR. In August 2023, the tender was awarded to Jäger Elektronik; in the meantime, the design phase is almost completed.

The nc-dipoles require special alignment supports, which can be remotely mechanically regulated in order to adjust the position of the 90-ton dipoles with submillimetre precision. In February 2023, the contract for manufacturing was awarded to Fantini Sud s.p.a., Italy. The company will produce also special remotely mechanical regulating alignment supports for the other components in target area, namely: one support for the target chamber; one for nc quadrupoles pair, one for nc quadrupole-sextupol pair, two for two beam catchers, one for beam catcher-sextupol pair. In 2023, Final Design Review (FDR) for all supports was completed; currently production is running. Alignment supports are the first components that must be installed in target area.

Remotely regulating supports are needed because components in target area are housed in a closed narrow tunnel, completely shielded by iron and concrete to protect the environment from radiation. Iron blocks for the lateral shielding, produced in 2021 by Walzengießerei Coswig GmbH, Germany, will be installed in spring 2024. The tender for contracting a company to install them is in the awarding phase. The production of iron shielding inside the tunnel, which protects the entrance and exit of target area, and part of the iron roof over them, was awarded also to company Coswig, in October 2023. Iron roof was originally in-kind of India, which however withdrew its contribution in September 2023.

Figure 115. Production of beam-catcher chamber at Trident Auto Components Priv. Ltd., India

After impinging on the target, most of primary beam will be stopped by three beam catchers (BC) placed after each dipole. A beam catcher is composed by a large vacuum chamber inside which water cooled absorbers are placed. The upper part of the chamber is filled with steel shielding, while on the lower part beamline components are mounted on the removable shielding plugs. Beam catchers are assigned as Indian in-kind contribution. In 2023, the Indian provider awarded the production to company Trident Auto Components Priv. Ltd., India, which already started the production both for chambers and plugs (Figure 115).

Since until 2022 a timely delivery of BC from India was questionable a Plan-B procurement of the chambers was started since these chambers are essential for the installation plan. NTG Neue Technologien GmbH & Co. KG, Germany was awarded with that and the CDR was completed in 2023.

Based on the design done by the University of Groningen (KVI-CART) in the Netherlands, the manufacturing of the target chamber was awarded to Fantini Sud S.p.A., Italy. In 2023, the industrial design (FDR) was completed; in June 2023 the production started and it is running speedily.

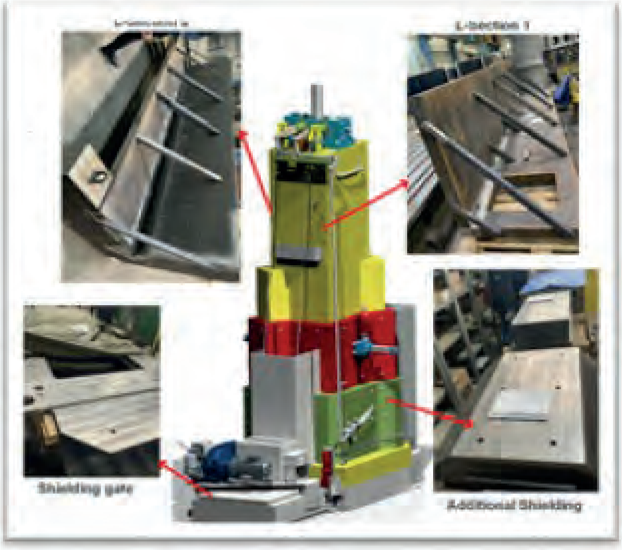


Figure 116. Production of the transport flask at Bilfinger Noell GmbH (BNG), Germany

Activated plugs and targets will be removed from the beamline by a transport flask , which will deposit them in a hot cell. Flask is being produced by Bilfinger Noell GmbH (BNG), Germany. In 2023, manufacturing of main components was successfully concluded (Figure 116); the production is now in pre-assembly phase. Due to its large dimension – the flask is more than 6 meters high – the final assembly, planned for the second half of 2024, will be done directly inside the target-area building.

The closure of beam vacuum in the highly shielded area requires specially developed components. Special removable plugs with integrated pillow seals will be placed in-between neighbouring components. In October 2023, the production of 10 plugs was awarded to company Asturfeito, Spain. In January 2023, the production of 10 pillow seals was awarded to company MEWASA, Switzerland; the design (FDR) was completed in May 2023, and the production is running.

Superconducting magnets system

Figure 117. Storage of sc magnets at ASG, Italy

Before and after target area, the beam line is composed by superconducting (sc) magnets. The beam line up to the experimental area for "early science" comprises 15 sc dipoles and 20 sc multiplets. A multiplet is a unit embedding several sc quadrupoles and various corrector magnets.

Sc multiplets are being produced by ASG Superconductors S.p.A, Italy. In 2023, the series production was running speedily until systematic leaks in thermal shields were detected at cold. These leakages are not detectable at warm, therefore could not be identified during construction and in the Factory Acceptance Test (FAT). Although all magnetic measurements were successful, demonstrating the expected physical functioning of the magnets , leakages would not be sustainable in the operation phase. The second half of the year was devoted to investigate the cause of leakage, which finally was envisaged to be related to brazing joints and thermal stress exposure. Because of this, the production of magnets and other components could continue (Figure 117), but the final assembly was set on-hold. Technical solutions to solve the problem were found, and the repair of affected multiplets is ongoing, and will be tested again at cold during 2024. If tests at cold are successful, as reasonably expected, we will still achieve the planned installation schedule.

Sc dipoles are being produced by Elytt Energy, Spain. As well as for sc multiplets, sc dipoles showed similar leakage problems at cold related to the meanwhile improved brazing method. Reparations are running, and testing at cold will be started again in March 2024. There are two types of sc dipoles depending on their bending (namely 11° and 9,75°). The magnetic field quality of one type of dipoles was successfully measured; the magnetic measurements of the second type of dipoles will start in March 2024. Like for sc multiplets, the physical functioning of the dipoles is not an issue.

Cold tests and magnetic measurements of sc magnets (corresponding to Site Acceptance Test, SAT) are done at CERN, where we built a devoted test facility in collaboration with the cryogenic expertise at CERN. The facility consists of three test benches, in order to increase the testing rate of magnets. In August 2023, the expiring Collaboration Contract with CERN was extended. In order to analyze and tackle the issues with thermal shield leakages, task forces GSI-Elytt/ASG-CERN have been established and are operating with great success. Especially improved quality assurance methods like multi-perspective x-ray images of brazing joints, that have been developed at CERN, allow for a better process surveillance, prior to final installation of the magnets, and will help to avoid further surprises appearing at the cold tests.

Once tested at cold at CERN, sc magnets are shipped to GSI. Before the installation in tunnel, the sc units must be finalised by integrating some add-on parts (an activity called pre-assembly). Since 2022, pre-assembly takes place in a dedicated area at GSI. In 2023, the pre-assembly work continued for those multiplets that showed no leakage issues. At the moment, the pre-assembly work is completed for six multiplets that are stored at GSI. The documentation work - like instructions for installation in tunnel - is ongoing.

Whereas sc multiples integrate the vacuum chamber, chambers of sc dipoles are purchased separately and will be integrated in the dipoles during the pre-assembly before installation in tunnel. All vacuum chambers were originally assigned to Russia as in-kind contribution; actually, they are purchased via tenders at industry. There are three main types of sc-dipole vacuum chambers: one for the 11° dipoles, and two for the 9,75°. Two first-of-series (FoS) sc-dipole vacuum chambers (one 11° and one 9,75°) were awarded to Omega Physics, Germany, in 2022. In 2023, both CDR and FDR were approved, at the moment production is running, and delivery is planned for spring 2024. The second type of 9,75° chamber has a special Y-forked shape, being the dipoles located at the branching points. In 2023, specifications for tender were completed, and tender is running at the moment.

During operations, the magnetic field inside sc dipoles will be measured by means of devoted field monitoring system that comprises Hall-probes and NMR-probes. The magnetic-field monitoring system is an in-kind contribution of Sweden, Lund University. In April 2023, the specifications were completed, and the in-kind contract is being adapted to the Early Science scope.

The operation of sc magnets requires a cryogenic facility. At FAIR there is only one central big cryogenic plant which feeds the individual local cryogenics (see devoted contribution of Department Cryogenics (CRY) to this annual report). The Local Cryogenic (LC) system of Super-FRS is composed of several cryogenic branches. A branch is a system of interconnected feed boxes which cryogenically supply the multiplet and dipole magnet cryostats by mean of an interface component called jumper. The design, production and installation of the LC branches is Polish in-kind of the Wrocław University of Science and Technology (WUST). The large majority of the conceptual design works for all branches have been concluded throughout 2023. The first part that will be installed is the branch before the target area (so called branch T). In September 2023, WUST awarded the tender for the production of branch T to INOX India Ltd. The components of branch T will also act as "first of series"; they will be carefully tested in a devoted test facility at FAIR campus prior their installation. The tendering for production and installation of the remaining Early-Science Branches has been started or is in preparation.

The cryogenic branches are connected with the Auxiliary Cryogenic Piping System (ACPS). The ACPS consists of three subsystems of piping lines, for a total of about 1,2 km, that run parallel to branches. The 3 subsystems are: The Multi-Purpose Line (vacuum-insulated 5 K to 300 K return header used as quench buffer, and for individual magnet cryostat cooldown and warmup), the Warm Gas Supply (a 300 K helium supply header for purging, and for the cooldown and warmup of individual magnet cryostats) and the Current-leads Gas Return (a 300 K return header for the magnet cryostats' current-leads return gas). Due to space constrains in tunnel, the ACPS has to be installed before the LC branches, at the end of 2024, therefore at relatively early stage of the whole Super-FRS installation. In June 2023, after successfully revision of the specifications of the ACPS, that was originally assigned to Russia as in-kind contribution, the production was tendered to industry, with particular focus on matching the tight installation time constraints. The tender will be awarded in February 2024.

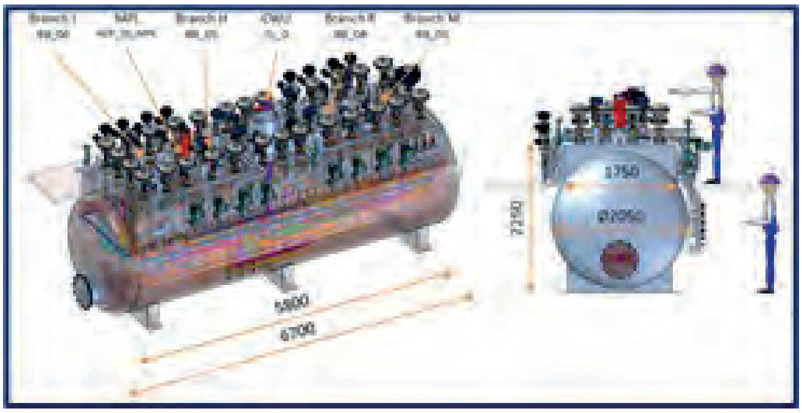


Figure 118. CDR of Branch Box, Demaco Holland, the Netherlands

Another key component for the local cryogenic system is the Branch Box, which distributes cold helium to and from the FAIR cryogenic plants and the Super-FRS experimental branches. The production of Branch Box, originally Russian in-kind contribution, was awarded to Demaco Holland, in April 2023. In November 2023, the CDR was approved (Figure 118) and the final design is well advanced. The 2 Branchbox branch connections, also former Russian in-kind, will be contracted with WUST as part of the polish in-kind, after successful negotiations.

For the powering of the sc magnets for early science 116 power converters (grouped in 58 cabinets) are required. All power converters were originally Indian in-kind contribution. In 2023, India expressed its will to withdrawn the power converters for quadrupoles and dipoles. After a re-adaptation of the specifications for industrial tender, the FAIR tender started and it is now in the awarding phase. The power converters cabinets will integrate also the electronic units for quenching detection/protection (produced by Semicon z.o.o. in Poland). The 55 corrector power supplies remain as Indian in-kind contribution.

Vacuum and beam diagnostic systems

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. The first two diagnostic chambers were produced by Pfeiffer Vacuum Components & Solutions GmbH, Germany, in 2022. The SAT was successfully concluded in January 2023. These two chambers serve as test benches for Super-FRS diagnostic elements (slits systems and different detectors).

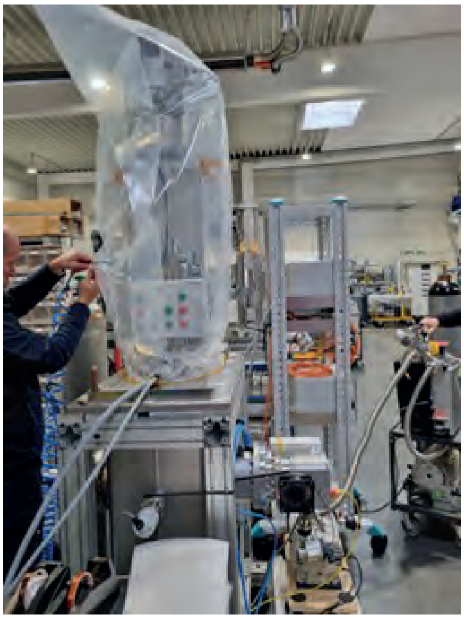


Figure 119. SAT of beam stoppers, produced by Axilon AG, Germany, at GSI campus

In 2023, the production of two Beam Stopper Systems by Axilon AG, Germany, was successfully concluded. In December 2023, they were shipped to GSI; the SAT started and it is currently ongoing (Figure 119).

Several detectors are produced in-house at GSI. Among these, for early science, plastic scintillators are developed as replacement of time-of-flight detectors, which were originally Russian contribution. The CDR of plastic scintillators was approved in March 2023; one FoS detector was build and will be tested with beam from beginning 2024. Other former Russian contributions are the diamond detectors and the beam-position monitors. The GSI development of diamond detectors is advanced: the possibility to use technologies other than polycrystalline diamond were investigated, and the associated CDR is in preparation. Beam-position monitoring before target will be now performed with ionization profile monitors (IPM), a technology adapted at GSI and being used in the whole FAIR accelerator system. The development of dedicated IPMs is concluded, the design was adapted to the diagnostic chamber; mechanical parts and other components were ordered. Time Projection Chambers (TPC) are planned as high-performant tracking detectors all along Super-FRS, as in-kind contribution of Finland. For the ES objective, the Helsinki Institute of Physics will be able to contribute with up to 5 detectors; the CDR for these detectors was conditionally approved in November 2023. In order to cover the full scope with current time restrictions, a set of tracking detectors for early-science will be produce in-house at GSI. The related developments of scintillating fiber tracking detector systems are already well advanced .

Finland is also producing the ladders for position detectors; the CDR was approved in January 2023; at the moment two FoS drives are under construction. Sweden is contributing to Super-FRS detector system too. The in-kind contract for design and production of drives was signed in January 2023. Key parts of this component are the M-Boxes and the power-drive controller (PDC). The CDR of both parts was approved and production is running. The experimental data acquisition (DAQ) for Super-FRS diagnostic components is in-kind contribution from

Sweden, Chalmers University. The goal of this part of data acquisition is to read out the detectors from Super-FRS in a synchronized way, permitting particle identification in the spectrometer; this is done using the NUSTAR Data Acquisition standard (co-jointly defined with the NUSTAR collaboration). The information can then be synchronized in a particle per particle basis with the NUSTAR experiments. The Chalmers contribution to Super-FRS comprises a Signal Exchange Points, electronic modules assuring a synchronize logical signal fan-in–fan-out with optical fibres throughout the separator and experimental branches. At the time project started, commercial solutions did not exist for the high concentration of input-output requested and a prototype has been developed and successfully tested. Meanwhile, potential industrial solutions have appeared. Therefore, in 2023 a new concept was started to be developed based on the commercially available solution (COTS) which will assure an improved long-term availability of the hardware part of the solution. The required firmware, comprising the synchronization protocols and logics, a will still be developed at Chalmers University. Another contribution of Sweden is the electronic of the Beam Loss Monitors (University of Lund), which monitor beam deviations from the beam line. The in-kind contract was signed in July 2023.

Additional steps were taken also in the design and procurement of components needed to close the beam vacuum. The final comprehensive vacuum system for the whole Super-FRS was defined . Twenty special inflatable bellows are required in beam locations with tight access. The specifications were approved in August 2023, and the following tender was successfully concluded by the award to the company MEWASA, Switzerland, in November 2023. Among the purchase of standard vacuum components, several frame contracts were awarded during 2023, as those for gauges (Inficon, Germany), turbo pumps (Leybold, Germany), ion getter pumps (Agilent, Germany).

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

Head: Stefan Menke
Authors: Ralph Bär, Marcus Schwickert, Andreas Reiter, Holger Kollmus, Ina Pschorn, Horst Welker, Martin Eibach, Frank Hagenbuck, Carsten Mühle, Lukas Urban, Christina Will, Stefan Zeller, Mario Bevcic, Andreas Krämer

Dept.: Accelerator Controls System (ACO)
Dept.: Beam Diagnostics (BEA)
Dept.: Cryogenics (CRY)
Dept.: Engineering (ENG) – Normal Conducting Magnets (NCM) – Survey & Alignment (S&A)
Dept.: Electric Power System (EPS)
Dept.: High Energy Beam Transport (HEB)
Dept.: Transport and Installation (TRI)
Dept.: Vacuum Systems (VAC)

Dept Accelerator Controls System (ACO)

Author: Ralph Bär

The accelerator control system for FAIR, including the GSI injectors, is being designed and developed as In-kind contribution of the GSI Controls Group with contributions from the Slovenian Tehnodrom consortium. In line with the overall development and implementation strategy of the FAIR control system, the focus in 2023 remained on the implementation, testing and commissioning of the future system at the existing GSI injector chain (SIS18, ESR, CRYRING, GSI-HEBT) for FAIR Phase 0.

Since the complete replacement of the old GSI accelerator control system (except UNILAC) by the FAIR control system in 2016-2018, the new system was successfully operated in four regular beam times in 2019 till 2023. This allowed to execute rich experimental physics programs with all machines.

After the successful implementation of underlying development frameworks and the implementation of basic operational functionality for synchrotrons, storage rings and beam transport lines, the main efforts in 2023 were concentrated on rolling out further functions and improving overall system performance. Thus, a basic version of the FAIR control system is already in use and in operation for the FAIR Phase-0 beam times today, ahead of the commissioning of the new FAIR machines.

Architecture, basic concepts and general system design have still so far shown no fundamental problems or showstoppers. Central systems of the control system architecture show a reliable and stable operation. Nevertheless, some minor technical and performance limits could already now be identified in individual controls subcomponents during commissioning and operation. The subsequent technical revisions or re-designs of these subsystems required, are, however, identified early enough to be mitigated and none are considered as critical in the FAIR project neither from a technical nor from project schedule execution perspective.

Moreover, significant progress has been made in 2023 on all control system subprojects. Highlights are:

Archiving System

The Archiving System is the measurement database system of the accelerator control system that persistently stores mass measurement data from all kinds of accelerator components and subsystems. A first implementation was already in experimental use during beam time 2021 for testing. After revising operational experience and key performance parameters a substantial revision of the system was carried out in 2023. This includes the complete replacement of the underlying real-time database technology due to software licensing issues (change from Elastic Search to OpenSearch real-time database). The upgraded system was rolled out in January 2024 and is planned to be extensively tested during the upcoming beam time 2024.

Sequencer Service and Application

The sequencer service within the accelerator control system helps to define and automate test procedures and is an efficient tool for hardware and beam commissioning. Within 2023, the protype sequencer was further developed and implemented as a central software service, that can now be accessed by several instances of the sequencer graphical user applications. This allows to execute automatic sequences in parallel and generate automatic test reports. Existing sequence definitions were migrated to the new system and used by operation for beamline and beam commissioning.

FAIR Timing System

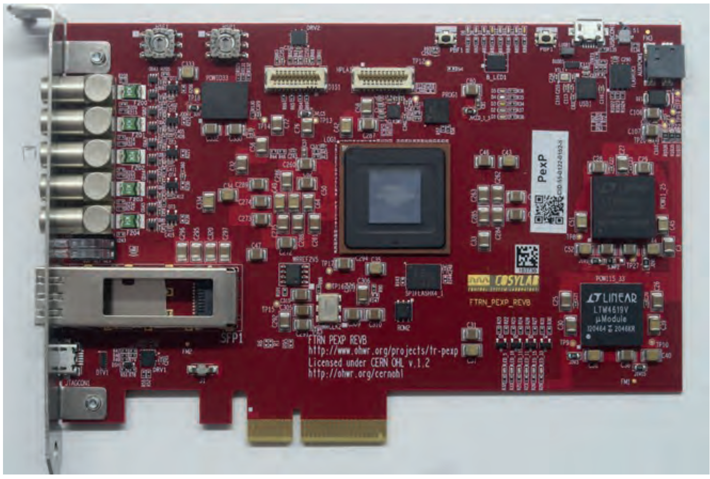


Figure 120. FAIR Timing Receiver in PCIe form factor (PexP)

Electronic timing receiver boards in PCIe form factor (PexP) for the FAIR White Rabbit based Timing System were successfully designed and developed in 2023 together with the Slovenian in-kind partner Cosylab. These electronic boards decode the White Rabbit timing telegrams and provide high-precision triggers to DAQ systems and software interrupts to real-time embedded controllers. The PexP timing receivers are essential parts for the FAIR beam instrumentation data acquisition systems and needed for system integration. By end of 2023, all 637 timing receivers were produced, delivered to GSI/FAIR and successfully tested. This completed the delivery of all electronic timing receivers in all form factors for the FAIR project.

Personnel Access Control System (PAS)

During the second half of 2023, significant progress in the development of the Personnel Access Control System for FAIR has been made. The electrical and mechanical planning of all PAS cabinets, terminal boxes and operating panels for the gates were completed and awarded for production. Personnel Access Gates (PAG) have been fully specified and the procurement started. The software development of integration and driver development for the RFID system, of dosimeter readers and of hand vein scanner systems has substantially progressed. The network and communication matrix for all components and network services of the PAS has been fully defined as base for implementation. Finally, all safety components for the stage Early Science (ES) have been fully defined and are procured in 2023.

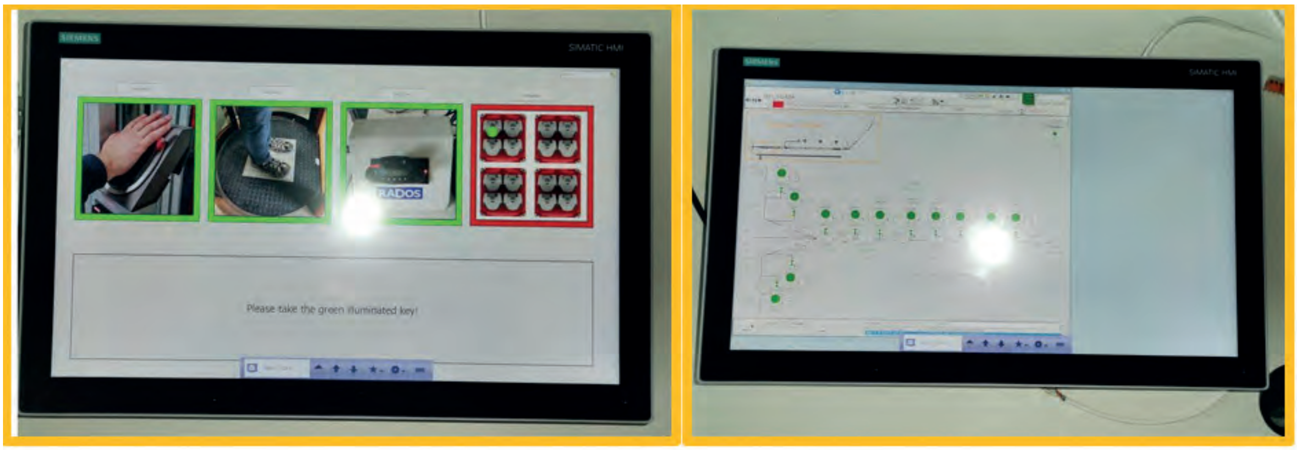


Figure 121. Gate UI concept (Personnel Access Gate)

Dept.: Beam Diagnostics (BEA)

Authors: Marcus Schwickert and Andreas Reiter

In 2023, BEA department concentrated its efforts on the first two FAIR stages, Early Science (ES) and First Science (FS), as defined in the review report from the Committee for First-Science and Staging Review of the FAIR Project in October 2022. The BEA work packages for anti-proton target and collector ring were suspended. The same applied for works on the proton linac (pLinac) after conclusion of final beam tests and acceptance of all delivered SEM-grids.

Last research activities for the pLinac were completed with SEM-grid measurements of beam profiles at the UNILAC dedicated to cross talk investigations that are relevant for emittance measurements, especially for small beams. During dedicated machine experiments, data were taken with the FAIR standard multi-channel hardware for profile measurements with SEM-grids or multi-wire proportional chambers (MWPC). Another independent profile measurement test setup was successfully commissioned at UNILAC for the development of a data acquisition (DAQ) software according to the new FAIR standards. In terms of beam structure, beam intensity and repetition rate, this test bench complemented the already existing test setup at the HTP high-energy beam transfer line for beams of fast or slow extraction from the SIS18 synchrotron.

The longitudinal phase space of UNILAC received increased attention in the continued effort to improve linac performance and beam matching to the SIS18 synchrotron in order to increase multi-turn efficiency. Accordingly, the required beam instrumentation, consisting of fast Faraday cups (FFC) and Feschenko bunch shape monitors (BSM), was further upgraded. A major milestone was to perform the timely repair of one BSM accomplished by Forschungszentrum Jülich and the following re-commissioning at UNILAC before the start of the machine experiment runs.

In SIS18 synchrotron and high-energy beam transfer lines, FAIR Phase-0 investigations on spill structure and extraction optimization continued with a number of machine experiments [1].

Furthermore, investigations on detectors and front-end hardware, e.g. new plastic scintillator assembly, investigation of inorganic doped ZnO screens [2] or tests of current-to-frequency converter units were performed. The new ionization profile monitor (IPM) of SIS18, which is a prototype for the SIS100, operated for the first time with a new readout software according to FAIR standards, which was developed by Slovenian in-kind partners. Successful beam measurements generated valuable input for the further development, specifically the protection of the sensitive detector during operation with different beams.

An improved cryogenic current comparator (CCC) was installed in the HTA cave at the high-energy beam transfer line and successfully tested with slowly extracted beams from SIS18. The campaign will continue during the 2024 user beamtime and aims to finalize the design options for the FAIR CCC detectors [3], [4] that will be installed in the high-energy beam transfer lines of FAIR (HEBT). Procurement of a more powerful Helium liquefier was started in 2023 for the next upgrade of the CCC infrastructure.

Further, two new FAIR-type DAQ systems including readout software were added for beam position monitors (BPM) and fast current transformers (FCT) in the high-energy beam transfer lines. By now, prototype DAQ systems for all detectors required for commissioning of the first stages ES and FS have been tested or even installed in the existing GSI accelerator facility. These developments are also relevant in view of the intermediate completion of the new FAIR control centre FCC. An overview on μTCA DAQ systems is given in [BEA5]. First beam tests were used to commission BPM and FCT systems in preparation of beam physics studies during 2024. One such study aspires to compare the measured beam trajectory between SIS18 and ESR storage ring with the theoretical accelerator model for the beam line settings.

Finally, the completion of two PhD theses in 2023 on radiation hard scintillators and on CCC development carried out at GSI and both passed with honours, illustrates the high quality of recent work and scientific experiments, not only on these topics.

Concerning the preparation of FAIR installations, critical procurements could be concluded, e.g. the coating of ceramic gaps for current transformers and the mechanical BPM housings. An important milestone for the preparation of the SIS100 installation was reached with the successful site acceptance tests of the final batch of SIS100 cryogenic BPMs. By the end of 2023 all 86 ceramic BPMs had successfully passed cryogenic, high-voltage and radiofrequency tests, thus completing the full delivery of SIS100-BPMs. In addition, the design work for SIS100 Schottky pick-ups, based on electromagnetic simulations, has been completed so that procurement can now be started at the beginning of 2024.

All current transformers and BPMs for Early Science were assembled and tested. Series production of MWPC detectors at the GSI detector laboratory have continued throughout the last year. Several technical challenges were overcome, and the completion of a first batch of detectors is expected in 2024.

Almost all actuators were prepared for installation and the alignment carried out in their respective vacuum chamber ports. Just the pneumatic actuators for particle detection counters (PDC) still require the mechanical integration of secondary-electron monitors (SEM) on the pneumatic drive. SEM series production for Early Science will soon be completed by the BEA department itself. First vacuum chambers for HEBT IPMs have been delivered to GSI, while the first series delivery of HEBT IPM detectors is expected in February 2024 with the final delivery planned for April 2024. With the availability of these components work on larger assembly groups mounted on modular stands has commenced. After final acceptance, first assembly groups will be transported and installed on FAIR site in the first quarter of 2024.

- [1] P. Niedermayer et al.,"Investigation of micro spill in RF KO extraction using tailored excitation signals", TUPM094, and J. Yang et al., "Study on spill quality and transit times for slow extraction from SIS18", TUPM097, Proc. IBIC 2023, Venice Italy, 2023
- [2] M. Saifulin et al., "Multi-Tile Zinc-Oxide-Based Radiation-Hard Fast Scintillation Counter for Relativistic Heavy-Ion Beam Diagnostic: Prototype Design and Test", TUP035, Proc. IBIC2023, Saskatoon, Canada, 2023.
- [3] L. Crescimbeni et al. "Cryogenic Current Comparator (CCC): Absolute beam current measurement in the order of nA", Proc. IPAC2023, THPL097, Venice, Italy, 2023.
- [4] T. Sieber et al, "Cryogenic Current Comparators as Low Intensity Diagnostics for Ion Beams", TUP036, Proc. IBIC2023, Saskatoon, Canada, 2023.
- [5] T. Hoffmann et al., "Status of the MicroTCA Based Beam Instrumentation DAQ Systems at GSI and FAIR", Proc. ICALEPCS2023, MO4AO07, Cape Town, ZA, 2023.

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 smaller 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 assigned to the FAIR sub-projects 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 60.000 hours 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. Main activities in 2023 were the cool down of the so-called string, an assembly two SIS100 dipoles and one SIS100 quadrupole module, and further testing of SIS100 quadrupole modules. The assembly of the string was very important to familiarize with the integration work at the intersections, in particular with regard to the high design pressure of 20 bar, and the applied test pressure of 28 bar. The string passed all pressure tests and a successful cool down was performed afterwards.

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

Figure 122. Delivery of the cold box CRYO2 to FAIR

After delivery of the bid central Cryo plant CRYO2 to FAIR end of 2022, the cold box, the distribution box DB3 and the compressor system are completely installed and all tubing is done in the meanwhile. Mechanical completion was reached in August 2023 including the installation of the cold box and DB3 (Figure 123) and that of the compressor system (Figure 124).

Figure 123. Cold box and DB3 installation after mechanically completion

Commissioning is scheduled for beginning of 2025, after all technical infrastructure like electrical power, water cooling and pressurized air will be available, with an expected completion time of up to 10 months.

As far as the Helium warm gas storage is concerned, the first 6 tanks have been produced and will be installed in February 2024. Afterwards they will be filled with 10,000 m3 of Helium, covering the demand of the CRYO2 commissioning.

Figure 124. Compressor system for CRYO2 and CWU

The Cryogenic Distribution Systems

Figure 125. 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. Most of them are a German in-kind provided by GSI, except a few parts provided as FAIR contribution executed by GSI.

For the SIS100 distribution system all parts were produced until early summer 2022 and installation of the complete system finished in October 2023. Figure 126 shows a part of the distribution system during installation with the DB4 distribution box and the transfer lines to the feed box of SIS100 in niche 5. The last remaining pressure tests at 28 bar will be performed beginning of 2024.

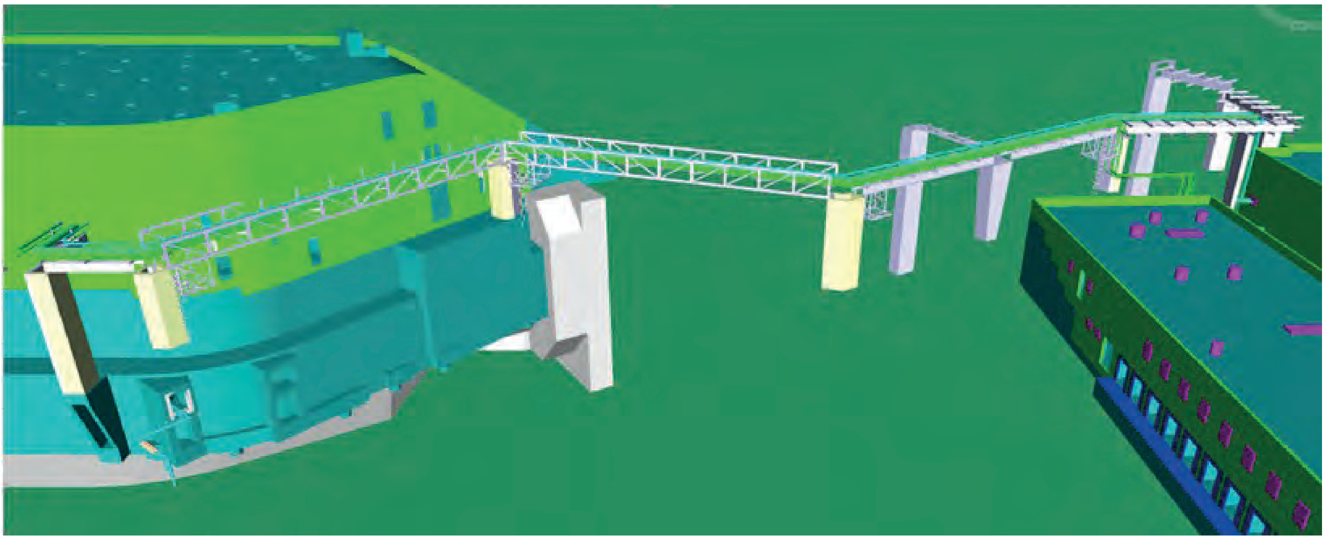


Figure 126. Cryogenic north/south connection to supply the Super-FRS and CBM

For the Super-FRS distribution system, the largest components are in the final stages of the specification phase. In February 2024, the rest of the Super-FRS distribution system will be put out to tender, with contract award expected in early summer 2024. Installation will follow in early 2025 in parallel with the commissioning of the CRYO2.

As the SIS100 and the Super-FRS machines are supplied by the same refrigeration plant, a sophisticated external route is required to connect the two buildings. Figure 125 shows the latest status of the external route bridge.

It carries the multiple cryogenic line for the supply and return of the 4-5 K and the 50-80 K temperature levels, a vacuum-insulated single line and the warm gas pipework to the CWU.

These lines connect the CRYO2 with DB2 close to the Super-FRS target region and supply the T-Branch and the P-Branch of the Super-FRS as well as CBM.

Other parts of the Super-FRS distribution system, like the transfer line between CWU and Super-FRS branch box are in procurement.

Dept.: Engineering (ENG) – Normal Conducting Magnets (NCM) – Survey & Alignment (S&A)

Author: Ina Pschorn

With the machine installation of some areas of the HEBT and the SIS100 set for January 2024, the metrological framework for correct initial positioning of the accelerator components in the tunnel of the assigned FAIR areas, initially only with millimeter precision had to be created in 2023.

A measurement infrastructure was first set up in the accessible and suitable FAIR accelerator tunnels and installed in form of unique survey points. These represent the base point network for accelerator measurement and alignment. Due to their function as orientation points for the subsequent fine alignment of the installed accelerator magnet sections in the accuracy range of +/-0.1mm, these points should not be confused with references for the construction survey.

In addition to the comprehensive determination of the current geometric status of the UNILAC/TK, HEST and SIS18 machines, which as FAIR injectors must have an important spatial connection to the new floor and wall points in the FAIR tunnels,

the first high-precision 3D point network measurements were carried out in the SIS18 connecting tunnel to parts of the FAIR HEBT area by using a laser tracker, a mobile coordinate measuring system. Due to restrictions in accessibility of connecting tunnels during GSI beamtime, this was already done in May and June 2023.

In a second step, network measurements were also performed in larger HEBT areas in the direction of Super-FRS and in the complete SIS100 tunnel including injection and extraction in November 2023. Point coordinates were determined in the uniform GSI NN coordinate system with accuracies of better than ± 0.1mm. Such an absolute point accuracy of a few tenths of a millimeter can be guaranteed by doing network measurements only. Within the FAIR buildings, the nominal positions and heights of the accelerator components to be installed in the future can be adapted to reality and these nominal positions can be suitably marked on site.

In addition to these important first steps of accelerator measurement in the real FAIR buildings, a large number of high-precision 3D measurements for the fiducialization of magnets and diagnostic chambers, on cryostats and alignment devices, were carried out throughout 2023. A variety of geometric measurement services accompanied the setup and testing of the SIS100 string. For example, movements of the entire string structure in relation to each other and to outside references after cool down and warm up were metrologically determined, but also further long-term tests of the interferometric system for detecting movements of the cold masses within the cryostats were carried out there and are still being continued.

A significant part of the Survey and Alignment missions in 2023 included specifical advisory and conceptual work on all points relating to the alignment of all FAIR and GSI machines in the most general sense.

Dept. Electric Power System (EPS)

Author: Horst Welker

Machine cable management and User Cable

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

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

At the end of 2022, the company Electricity EOOD, Bulgaria, was contracted for the material and laying of the user cables. The cable installation started in 2023 to enable start of machine installation in Q1/2024.

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

The routing process is coordinated together with FSB. The design of machine trays finished for the HEBT and the completion for SIS100 and SFRS areas/buildings is expected in Q4/2024.

The specification for the installation of machine trays, assembly and connection of user cables has been released for the review process. This specification also includes grounding of components and electrical testing of components after cable connection.

FAIR representatives visited the Indian Company Siechem Technologies Pvt. Ltd. for the India In-kind cable delivery in June 2023 for CDR/FDR review, and consequently the FAT for the first batch of pre-series cables was successfully performed in Q4/2023.

EPS

To ensure a stable and reliable operation of the existing 950 power converters in GSI, several upgrade and refurbishment projects were realized in 2023. More precisely, the renewing of the power parts of the quadrupole power converters for the Fragment Separator using state-of the art components has been continued. In parallel their analog control systems were upgraded to digital ones based on the FAIR standards. The old Programmable Logic Controller (PLC) systems of the 20kV switchgear system for the main power converters of the SIS18 and ESR are envisaged to be exchanged by modern Siemens S7 systems. The preparation of this activity was performed in 2023, the realization will follow in the 2024 shutdown. 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 delivered, installed and the SAT was performed. Furthermore, 4 injection quadrupoles for the SIS18 were contracted as replacement for the present ones reaching their end of lifetime. 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. This involved the redesign of the set-value generation boards for the large driver cards of the parallel active filter units of the SIS18 and ESR main power converters, as well as the design and installation of a replacement analogue controller board for special linear controlled power converters (bumper, sweeper).

For the Alvarez Upgrade project, pulsed power converters were designed. Two converters were built and tested and shipped to the test facilities of the manufacturers of the corresponding magnets for testing.

Dept. High Energy Beam Transport (HEB)

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

In 2023, activities for the high energy beam transport system (HEBT) were characterized by processing of ongoing procurements, re-procurement of ex-Russian components and the preparation of pre-assembly and tunnel assembly in close collaboration with the sub-project Site Management (SMG). With regard to the FAIR buildings, main activities for HEBT were in the context of the spatial 3D-coordination of the technical building equipment of the northern FAIR buildings.

Magnets

In 2023, GSI has continued its role as manufacturer, completing various documents required for CE conformity for the Russian magnets.

Apart from documentation completeness and accuracy, significant attention was dedicated to the physical components themselves. GSI personnel have undertaken several complex adjustments and repair tasks, with the aim to ensure efficient assembly once the vacuum chambers become available.

Following the definition of scientific priorities, a list of magnets required for the three project stages Early Science, First Science, and First Science Plus configuration levels was compiled. To optimize costs, magnets initially designated for later stages of the project were identified and successfully reassigned. The remaining required 5 dipole, 43 quadrupole, and 14 corrector magnets, along with additional components, underwent a thorough specification and tender process within the year. Contracts for these magnets were awarded between September and December 2023, initiating straightway the design phase.

Power Converters

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

131 power converters for quadrupoles (6 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 and testing of the remaining units have started. The delivery of all these power converters is scheduled to be completed in the first half of 2024.

The series production of 53 power converters for dipoles and 8 power converters for quadrupoles by the company Jäger Elektrotechnik GmbH (Germany) is ongoing. So far, 27 power converters for dipoles (8 types) and 4 power converters for quadrupoles (1 type) have been tested and delivered to FAIR. The delivery of another 17 power converters is planned until Q3/2024. Due to their large power and size, the remaining 13 pulsed power converters will be connected to the 20kV supply system and will have to be assembled directly in the building. One associated 20kV transformer for these converters was delivered in 2022. The remaining 12 20kV transformers are expected to be delivered in Q2/2024.

Vacuum chambers

In 2023, the focus was on the re-procurement of the missing vacuum chambers for HEBT within the First Science Plus scenario.

The GSI design office realized the chambers' design of almost all work packages. In parallel the detailed specifications for the different chamber's types were reviewed, approved and the tender processes started. Considering pending decisions on realization of First Science Plus, chambers exclusively needed for this stage are requested as option for all types of chambers.

The round chambers for the quadrupole and steerer magnets of HEBT were awarded to SAES Rial (Italy) in June 2023. These chambers are currently in production and the first 6, needed for the quadrupole magnets of beam line section T1S2, will be delivered to GSI at the end of January 2024. In the same month, also with SAES Rial a contract for production and delivery of more than 300 bellows was signed. The first 50 standard bellows will arrive at GSI in mid-February 2024.

The rectangular dipole chambers were awarded to Fantini (Italy) in December 2023 and the design is well advanced. Also at the end of 2023, final negotiations on the pumping chambers took place, the contract will be awarded in the beginning of 2024.

Furthermore, the 68 straight beam line tubes required for Early Science were designed and manufactured in-house at GSI and undergone their final acceptance test.

Framework agreements for all standard components were concluded in 2023. In the meanwhile, all required ion getter pumps, ventilation valves and measuring gauges have been delivered and are ready for pre-assembly and tunnel assembly. The contract for all valves for GSI and FAIR was concluded at the end of 2023 with the objectives of stepwise delivery starting in Q2 2024.

Special Installations

The series production of the HEBT Diffusors, which are constituents of the Personnel Access System of FAIR, was completed by VA-TEC GmbH & Co KG in 2023. All eleven diffusors were tested successfully during their SAT and are now stored in Weiterstadt until installation in the respective assembly groups.

The production of the HEBT18 and HEBT100 beam collimation systems is conducted by COMEB S.r.l (Italy). After implementing design improvements, the delivery of the FoS product is scheduled for Q1/2024.

The graphite cores for the two HEBT Beam Dumps, located in the SIS100 injection and SIS100 extraction beam line, have been delivered and will be installed as soon as the building sections are prepared.

Special Stands

Due to delays in the finalization of remaining design issues, the FDR of the large support frame manufactured by Kraftanlagen Heidelberg GmbH in building H0705A was postponed to the beginning of 2024.

Regarding the modular stands for HEBT, the delivery of frames of the first group was completed in September 2023 by Nordisk Industrioptimering AB (Sweden)/BLEICHERT AUTOMATION GmbH Co.KG (Germany). GSI Design office completed the missing draft 3D-models and specification drawings for the modular stands of the second contract, that were handed over to BLEICHERT in October 2023. In the meanwhile, BLEICHERT started the design phase and the delivery of these frames is expected for mid-August 2024.

Furthermore, the GSI design office was responsible for the design of the stands for pumping chambers. In November 2023, 15 stands were awarded to Nortemecanica (Spain). The first 6 stands were delivered to GSI already one month later. Completion of delivery is expected for April 2024.

Dept. Transport and Installation (TRI)

Author: Mario Bevcic

During the shutdown 2023, TRI supported the Accelerator Operation Division (ACC) in service, reconstruction and upgrade of GSI-accelerator components and in the preparation of the planned beam time program. In particular, the repair of the ESR Cooler was one core activity of TRI, in parallel with numerous repairs on UNILAC, on HEST and SIS18. Also, the microspill cavity in SIS18 was transported and successfully installed.

Furthermore, TRI, together with the Site Management Sub-Project (SMG), was strongly involved in the development of transportation and installation concepts, tools and special devices for the installation of FAIR accelerator components.

Other efforts in focus were preassembly and preparation work on already supplied FAIR components, especially magnets for HEBT, SFRS as well as the support of testing and the preassembly of superconducting magnets for SIS100.

Dept.: Vacuum Systems (VAC)

Author: Dr. Andreas Krämer

For the FAIR project, the design of the vacuum system has continued with large parts finalized in 2023. Based on this, the specification and procurement of standard vacuum components like valves, vacuum pumps and gauges for the FAIR project have been accomplished in 2023. Hence, several calls for tenders were successfully executed. The supply of passive ion gauges of type cold cathode and Pirani incl. the required controllers were contracted with the company Inficon AG (Lichtenstein). Delivery of the first gauges is made and its installation has started in the assembly units of SIS100 and HEBT.

In addition, a contract for production and delivery of the gate and angle valves was concluded with VAT Deutschland GmbH, and another one for turbo molecular pumps with Leybold GmbH. The first components out of these contracts will be delivered to GSI within 2024.

Moreover, ion pumps, NEG pumps and extractor gauges each of them with corresponding controllers were delivered within 2023. This enabled to conclude provision of detailed information of components and their position in the cable data base, while the layout of the vacuum control system was continued. In that context, the Slovenian In-kind partner started with the electrical design and the first four of PLC cabinets were delivered by INEA end of 2023. The remaining ones for HEBT, SIS100 and SFRS will be delivered in 2024. Beside this, Natus GmbH & Co. KG delivered the first 67 solid-state racks,141 terminal boxes and 20 controls cabinets for the bake-out system of the room temperature operated vacuum sections in SIS100 and the direct neighboring vacuum sectors in HEBT at FAIR.

In 2023, also the vacuum acceptance tests as necessary quality control measures have continued in the vacuum laboratory. Various components for FAIR like HEBT beam diagnostic chambers of different manufacturers, HEBT diffusors, SFRS Multipletts and slits, were tested. Moreover, components for experiments and other installations in ESR, CRYRING and SIS18, and various material samples underwent acceptance tests in the UHV lab.

Further, VAC was involved in the installation of the ongoing SIS100 string tests and in the tests of SIS100 cryogenic magnet modules at the series test facility.

Likewise, VAC has invested a great deal of efforts in the maintenance and in shutdown works in the vacuum systems of GSI's existing plant.

Whenever a technical system or component installed in the beam vacuum of the accelerators has to undergo a repair or an upgrade, the vacuum system has to be vented. In the long shutdown 2022/23 the complete ESR vacuum system had to be vented. This was used to exchange all ion getter pumps together with their bake-out jackets, two large gauge valves and all bake-out jackets in the electron cooler. After all these intensive interventions, all four vacuum sectors had to undergo a bake-out cycle. Such as these interventions, all Titanium sublimation pumps were replaced by NEG cartridge pumps, during the upgrade and maintenance works in SIS18, increasing the pumping speed significantly. In CRYRING the electron cooler had to be repaired, also here a bake-out to reach the required vacuum level had to be prepared and performed by VAC. In HEST ion getter pumps were replaced by new ones, wherever a vacuum sector had to be vented. Finally, a lot of repair and maintenance works were also done in UNILAC.

Selected publications of 2023

- F. Amjad, C. Karagiannis, E. Kozlova, M. Duchene, H. Weick, “The Shielding Flask System at Super-FRS”, 8th High Power Targetry Workshop (HPTW2023), 6-10 Nov. 2023, Tokyo, Japan
- E.J. Cho et al., “Evaluation of Magnetic Performance of Super-Conducting Magnets for the Superconducting Fragment Separator at FAIR”, 28th International Conference on Magnet Technology (MT28), 10-15 Sep. 2023, Aix-en-Provence. To be published in IEEE.
- W. Freisleben et al., “Quench detection electronics for FAIR”, NIM A, Volume 1060, March 2024, 169040
- M. Alfonsi et al., "Validation of the Diamond Detectors for the Super Fragment Separator beam diagnostics", 16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23), 25-29 Sep. 2023, Siena, Italy. To be published in JINST.
- M. Czogalik et al., “Plastic scintillator fiber detectors for heavy ion trajectory reconstruction for the Super-FRS at FAIR”, 16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23), 25-29 Sep. 2023, Siena, Italy. To be published in JINST.
- N. Kurichiyanil et al., “Vacuum design of the Super-FRS at FAIR”, 14th International Particle Accelerator Conference (IPAC’23), 7-12 May 2023, Venice, Italy. To be published in J. Phys.: Conf. Ser. 2687 082031

12. Annex

All publications of the GSI in the year 2023 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 2023

complied by T. Beier & K.Füssel

Director's Board / Geschäftsführung

Prof. Dr. Paolo Giubellino, Dr. Ulrich Breuer / ad interim head: Markus Jaeger, 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 (up to May 2023) / Philipp Strauchmann, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany), as representative of the Federal Republic of Germany (since June 2023)

Stephanie Schinzel, Hessisches Ministerium der Finanzen, Wiesbaden (Germany),
as representative of the State of Hesse in Germany

Michael Braum, 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)

Jana Podßuweit, Thüringer Ministerium für Wirtschaft, Wissenschaft und Digitale Gesellschaft, Erfurt (Germany)

Dr. Andreas Gerhardt, Ministerium für Wissenschaft und Gesundheit Rheinland-Pfalz, Mainz (Germany), up to June 2023 / Miriam Hirsch, Ministerium für Wissenschaft und Gesundheit Rheinland-Pfalz, Mainz (Germany), since July 2023

Prof. Dr. Thomas Nilsson, Chalmers University of Technology, Göteborg (Sweden),
as Vice-Chair of the Joint Scientific Council GSI/FAIR

Prof. Dr. Thomas Glasmacher, Facility for Rare Isotope Beams, East Lansing (USA)

Prof. Dr. Cornelia Denz, Westfälische Wilhelms-Universität Münster (Germany)

Dr. Bettina Lommel, GSI Helmholtzzentrum für Schwerionenforschung,
as spokesperson of the Scientific-Technical Council of GSI

FAIR Council / Gesellschafterversammlung FAIR

Dr. Volkmar Dietz [chair up to 10/2023, vice from 10/2023],
Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany)

Dr. Catarina Sahlberg [vice up to 10/2023, chair from 10/2023],
Swedish Research Council (Vetenskapsrådet) (Sweden)

Dr. Andrea Fischer, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany),
as representative of the Federal Republic of Germany

Dr. Dirk Steinbach, Bundesministerium für Bildung und Forschung, Bonn/Berlin (Germany),
as representative of the Federal Republic of Germany

Dr. Christine Burtscheid, Hessisches Ministerium für Wissenschaft und Kunst (Germany),
as representative of the Federal Republic of Germany

Dr. Maxim V. Bogachev, 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. Uday Bandyopadhyay, Bose Institute,
as representative of India

Prof. Dr. Subhasis Chattopadhyay, Variable Energy Cyclotron Center (VECC),
as representative of India

Katri Huitu, Helsinki Institute of Physics, Swedish Research Council (Vetenskapsrådet),
as representatives of the Swedish/Finnish Consortium

Niklas Ottosson, Helsinki Institute of Physics, Swedish Research Council (Vetenskapsrådet),
as representatives of the Swedish/Finnish Consortium

Johan Holmberg, Swedish Research Council (Vetenskapsrådet),
as representatives of the Swedish/Finnish Consortium

Dr. Cornelia Anca Ghinescu, Ministry of Research, Innovation and Digitalisation,
as representative of Romania

Dr. Ruxandra Popescu, Ministry of Research, Innovation and Digitalisation,
as representative of Romania

Prof. Dr. Zbigniew Majka, Jagiellonian University Kraków,
as representative of Poland

Prof. Dr. Piotr Salabura, 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, UK Research and Innovation - Science and Technical Facilities Council (UKRI - STFC),
as representative of the United Kingdom

Dr. Helen Beadman, UK Research and Innovation - Science and Technical Facilities Council (UKRI - STFC),
as representative of the United Kingdom

Marek Vyšinka, Ministry of Education, Youth and Sports (MSMT),
as representative of the Czech Republic

Dr. Andrej Kugler, Nuclear Physics Institute of the Czech Academy of Sciences,
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12.2 Organisational chart