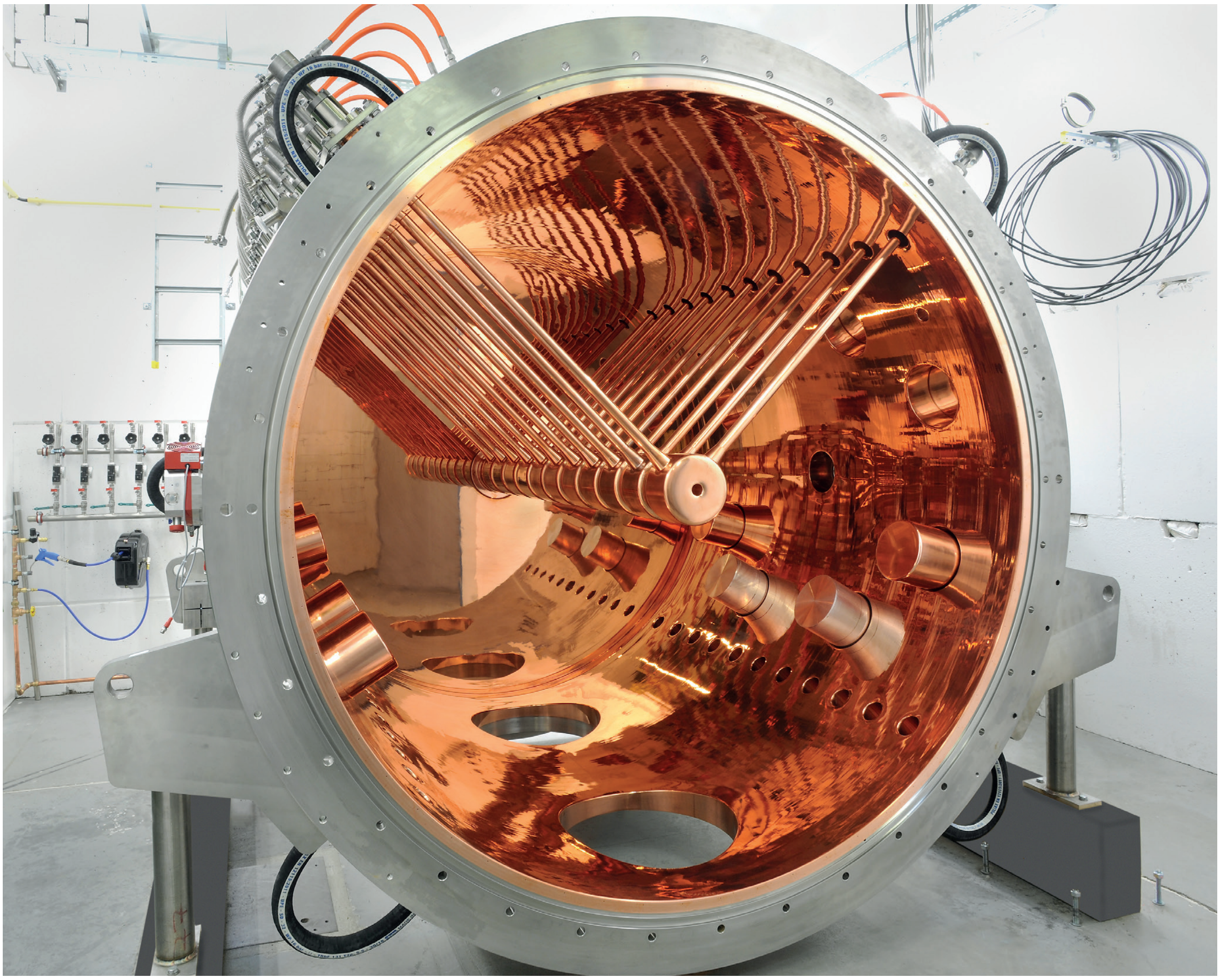
GSI REPORT 2022-1

GSI-FAIR SCIENTIFIC REPORT 2021

An overview of the 2021 achievements in science and technology



FAIR Phase-0 Research Program

GSI FAIR

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Completion of high-power rf-operation of first-of-series ALVAREZ cavity section:

After 45 years of operation, the old ALVAREZ-section will be replaced by a new post-stripper section. Its design is tailored to deliver intense heavy ion beams at high beam quality but also allows for provision of light ions as helium. Pulsed magnetic focusing elements provide optimized beam optics for each single ion species being delivered during quasi-simultaneous multi ion-species operation, a special operation mode of the GSI accelerators.

Prior to series production, all critical steps in cavity design, production, assembly, copper plating, and high-power radio-frequency operation have been successfully addressed. The cover shows the first-of-series cavity section of the ALVAREZ-type, being qualified in 2021.

See also page 122.

Text: Lars Groening

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FAIR Phase-0 Research Program

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Imprint

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Contents

1. Executive summary of research at GSI & FAIR

Coordination: Prof. Dr. Karlheinz Langanke (GSI)
Author: Yvonne Leifels

The FAIR Phase-0 program continued in 2021. The beam time started February 8th and ended July 16th. The beam time was slightly extended with respect to 2020 to allow scheduling experiments which could not take place in 2020 because of travel restriction due to the Corona pandemic.

The limitations arising from the Covid-19 pandemic, pose challenges to both, the operational team, as well as the experimental scientist involved in them. Given the strong restrictions imposed to international travel, the participation from external scientist from abroad is reduced to a minimum. The IT department undertook great efforts to significantly improve remote access to the experiments. Communication tools for video conferencing have been made available, remote control of experiments and remote access to experimental data have been significantly improved, such that external collaborators are able to actively participate in the beam times. The increased workload due to setting up the experiments was mastered by the local GSI staff together with participants from neighbouring universities. So far, experiment preparation and running is progressing smoothly.

Beginning of February all machines came into operation, including the complete operator chain to the CRYRING. High intensity carbon- and proton-beams have been produced out of one source and were utilized in parallel mode by the HADES experiment and the newly installed PRIOR II set-up in the HHT cave at SIS18.

Important achievements of this experimental campaign are reported in the following. One of the major highlights was the first experiment making use of heavy beryllium-like ions (ions with four electrons left in the outer shell) from the ESR injected into the CRYRING. In a first step the spectroscopy set-up to study dielectronic recombination DR in the CRYRING was taken into operation and Be-like $^{238}U^{88+}$was used for the subsequent experiment. Precision spectroscopy of Be-like heavy ions as test of strong field quantum electrodynamics QED. Another major step forward was the commissioning of the PHELIX beam line into the HHT cave. Laser pulses with energies >100 J were delivered to the HHT-cave, and synchronisation with the accelerator timing system was demonstrated. At the end of the beam time, the fusion reaction of carbon and helium to oxygen was investigated in the R3B cave. This important reaction for the production of oxygen nuclei in the sun was studied by Coulomb dissociation.

In autumn, the Time Projection Chamber (TPC) of the ALICE experiment at CERN was brought back to operation after a long upgrade phase. The GSI ALICE group, a team from the GSI Detector Laboratory together with partners from the German universities participated in the development and construction of new read-out detectors consisting out of Gas Electron Multiplier (GEM) chambers. This upgrade measure was supported by the Helmholtz Association in the framework of the Large Investment project “LHC Upgrade”. In late autumn, the performance of the upgraded ALICE detectors was verified with first proton-proton collisions.

The Forschungszentrum Jülich and GSI agreed to transfer the scientific responsibility of the Institut für Kernphysik (IKP), more specifically IKP-1, -2 and -4 as well as the technical/administrative services (IKP-TA), from FZ-Jülich to GSI with the start of the PoF-IV period on January 2021. One of the institute directors, Prof. James Ritman, has already moved from FZJ to GSI beginning 01.01.2021. Furthermore, first staff members and numerous IKP personnel on fixed-term contracts have switched to GSI, and all members of IKP will be offered to follow. Furthermore, the scientific managements of GSI and FZJ decide jointly on the assignment of beam time at COSY. Consequently, the open sessions of the fall COSY Beam Time Advisory Committee were opened to all members of GSI.

The organizational structure of the GSI research division has been extended by a new unit, FAIR Research @ NRW or FAIR Forschung @ NRW, FFN, which will serve as basis to formally integrate IKP-1 and IKP-2 into GSI. This novel organizational unit is directly linked to the research director of GSI on a similar level as the Helmholtz Institute

The Hessian state government is supporting cutting-edge research in Hesse with almost 40 million euros over a period of four years. Six projects will be supported in the funding line “Cluster Projects” launched by the state. One of the projects is ELEMENTS, which was proposed by the Goethe University Frankfurt, TU Darmstadt, which are equally leading the project, University Gießen and GSI. ELEMENTS will study the properties neutron stars. Neutron stars, like black holes, are the cause of extreme space time curvature because of their enormous weight concentrated in small volume. The merger of these objects are sources of detectable gravitational waves, but unlike black holes neutron star mergers allow conclusions on their interior and, therefore, the properties of dense strongly interacting neutron rich matter. Neutron star mergers and neutron star creation in the cause of a super nova explosion are predicted to be sources of heavy elements beyond iron via the so-called rapid neutron capture process (r-process), that involves reactions of unstable, extremely neutron rich nuclei. In 2017, the detection of gravitational waves of a neutron star merger together with the measurement of the light curve gave evidence that heavy elements are created during this event. Within ELEMENTS, dense strongly interacting matter as well as life-times, masses and reactions of extremely neutron rich nuclei will be studied at GSI/FAIR, thereby shedding light on the environment prevalent in neutron star mergers, in which heavy elements are formed by neutron capture reactions.

Also in 2021 GSI scientists received prizes and acknowledgements. As a particular highlight, Prof. Dr. Gabriel Martinez Pinedo was awarded with a Leibnitz Prize of the Deutsche Forschungsgemeinschaft 2022.

GSI, with exception of the Helmholtz Institutes and the Biophysics department, was exempted from the evaluation within the program oriented funding POF of the Helmholtz Association during the last funding period. 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.

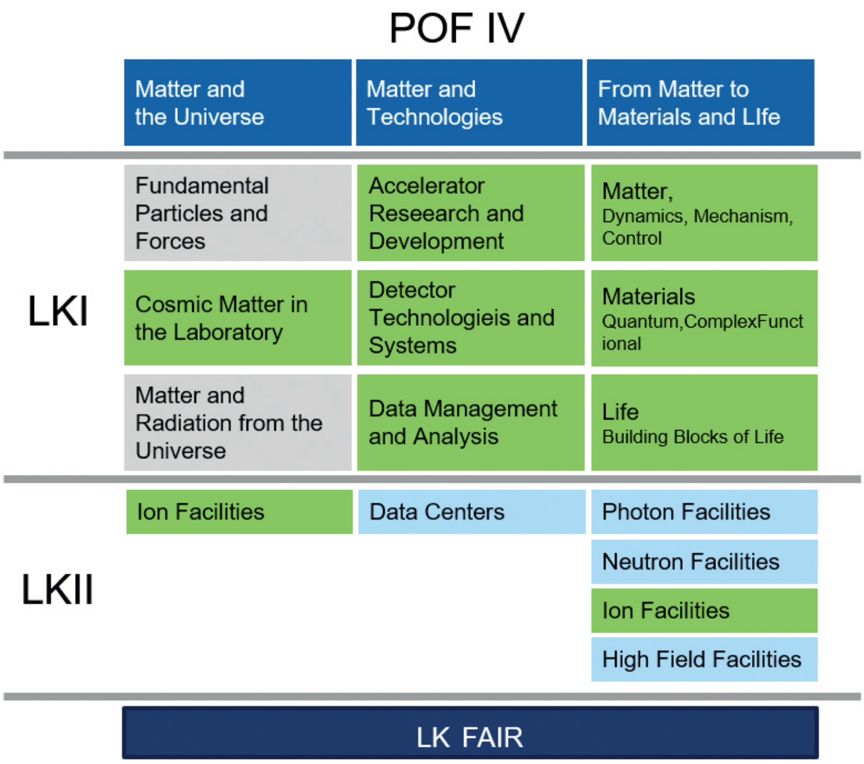

Figure 1. Structure of the Research Field Matter, which is divided into three programs (MU, MT, and MML). Each of the pro-grams comprises three LK1 topics and one or more LKII facilities. Topics, to which GSI is contributing are marked in green.

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 de-scribed not only in chapter "Research in accelerators, detectors, electronics and IT" but also in "Accelerator operations".

This report has been compiled and the results have been achieved before the Russian invasion into Ukraine in February 2022. In the meantime, collaborations with Russian institutions have been suspended in accordance with the Alliance of German Science Organizations. We are very saddened and shocked by the events and our thoughts go to all people who are directly or indirectly by the war in Ukraine. Many scientific results and technical achievements will be reported not only by GSI scientists but also international collaborators on the next pages. Not everything can be described to the extent actually necessary in the scope of the report and we would like to refer to our publication list at the GSI Repository.

User beam time 2021

compiled by beamtime coordinator Dr. Daniel Serverin

pro-posal number	experiment topic	spokes-person	main shifts	para-stitic shifts
E129	Photoionization of C+ ions at CRYRING	Jan Rothhardt	21	
E140	Absolute rate coefficients from dielectronic recombination for astro-physically important ion species	Michael Lestinsky	17	
E148	A Test of Optical Pumping at CRYRING	Rodolfo Sanchez	21,5	
E153	Multielectron recombination processes in He-like oxygen at the CRYRING@ESR electron cooler	Weronika Biela	17	
E125	High-resolution differential Measurements Between Two-and Three-Electron Uranium Ions for High-Precision Tests of Strong-Field QED (E125 resubmission)	Martino Trassinelli	19,5	
E143	Search for the nuclear two-photon decay in swift fully-stripped heavy ions	Wolfram Korten	13,4	
CMAT	Materials science experiments at CRYRING		5,3	
E131	Precision collision spectroscopy of Be-like ions at the CRYRING@ESR electron cooler	Stefan Schippers	22,3	
E138	E138 The Ground-State Lamb Shift in the Heaviest Hydrogen-like Ion (U91+): High Resolution X-ray Spectroscopy at the CRYRING Electron Cooler	Günter Weber	26	
E127	Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process	Rene Reifarth	13,6	
S440	Proton Microscopy of Underwater Electrical Wire Explosion	Joachim Jacoby	3,5	8,5

S452	The Prolate-Oblate Shape Transition around A~190	Volker Werner, Patrick H. Regan, Jan Jolie	19,5	
S455	S455: Fission investigated with relativistic-radioactive beams and the advanced SOFIA@R3B setup	Julien Taieb	19,6	14,7
S460	Investigation of 220<A<230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation	Giovanna Benzoni	16,7	
S470	Test of an HISPEC TEGIC detector for Low Energy Branch experiments	Stephane Pietri	2,8	
S483	Proposal for testing of beam instrumentation equipment for the Super-FRS at FAIR	Chiara Nociforo	8,6	19
S489	First combined laser-ion experiments at SIS18	Vincent Bagnoud		10
S494	Coulomb Dissociation of 16O into 12C and 4He	K. Göbel, M. Heil, R. Reifarth	42	
S496	Core-breaking in the most neutron-deficient Tin isotopes	Guangxin Zhang	29,4	
S511	FRS developments for NUSTAR experiments: Performance improve-ments and R&D work with heavy-ion beams	Christoph Scheiden-berger	13,3	
S514	mCBM@SIS18 2021/22	Norbert Herrmann		16
S515	Constraining energy-density functionals and the density-dependence of the symmetry energy by measurements of accurate cross sections with large acceptance at R3B	Thomas Aumann	17	19
S518	Electromagnetic formfactors of hyperons	Joachim Stroth	3	
S526	Direct mass measurements of heavy N=Z and N=Z-1 nuclides	Wolfgang R. Plass	9,5	

S529	Depth profiling of activity induced by heavy ions	Peter Katrik		3
S530	Fission isomer studies with the FRS	Timo Dickel	9	
S533	Measurements of nuclear and atomic interactions needed for ion-beam therapy with positron emitters of carbon	Sivaji Purushotha-man	14,5	
SBIO	Biophysics experiments at SIS18		18	
SMAT	Materials science experiments at SIS18		12,1	17,2
ERC	Experiments for BARB ERC Grant		14,5	
ESA	ESA irradiation experiments		15	
U311	Diffusive particle acceleration in a turbulent magnetized plasma	Gianluca Gregori		13
U316	Test of calorimetric low-temperature detectors (CLTDs) for the detection of heavy ions at intermediate and high ion energies for application in NUSTAR	Saskia Kraft-Ber-muth		8,2
U321	Laser spectroscopy of fermium, nobelium and lawrencium around N=152	Sebastian Raeder	18,1	46,3
U324	High-precision direct mass measurements of ground states and low-lying isomers in heavy and superheavy isotopes with SHIPTRAP.	Francesca Giacoppo	15	74,4
U327	Chemical studies of the superheavy element Z=115	Alexander Yakushev	82,8	16,7
U328	Final beam commissioning and first scientific experiments with an Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal (ANSWERS) setup at TASCA	Khuyag-baatar Jadambaa	13,1	22,7
UBIO	Biophysics experiments at UNILAC			6,9
UMAT	Materials science experiments at UNILAC		68	158

Table 1. ist of user experiments in 2021 and accounted beam time in 8h shifts. Secondary beam users get on the average 10 % of the available beam.

2. Research of the APPA Departments

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

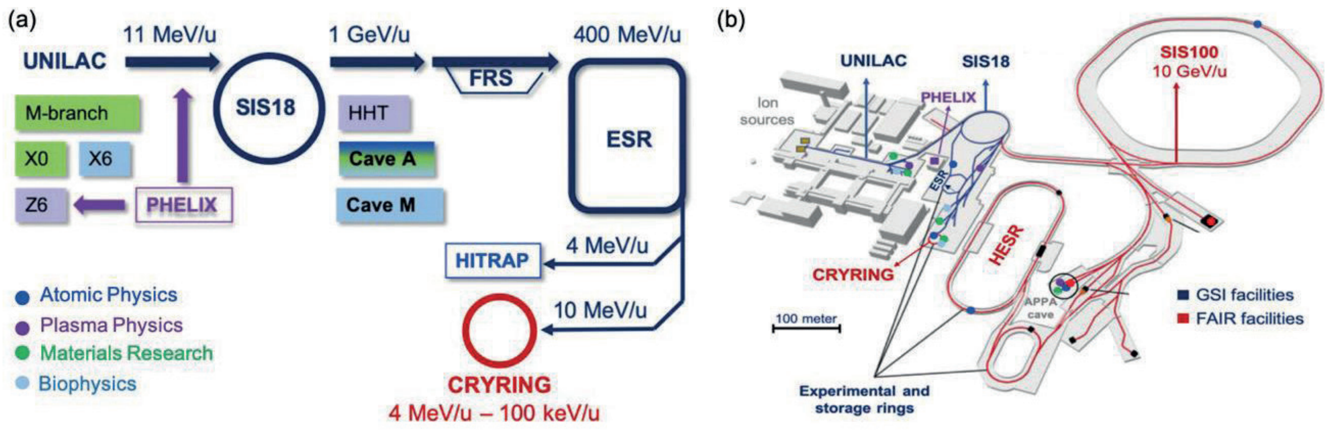

Figure 2.(a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (Th. Stöhlker et al., Nucl. Instr. Meth. B 365, 680 (2015)).

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 (MML/APPA research at GSI contributes to all three research topics of the program MML). 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.

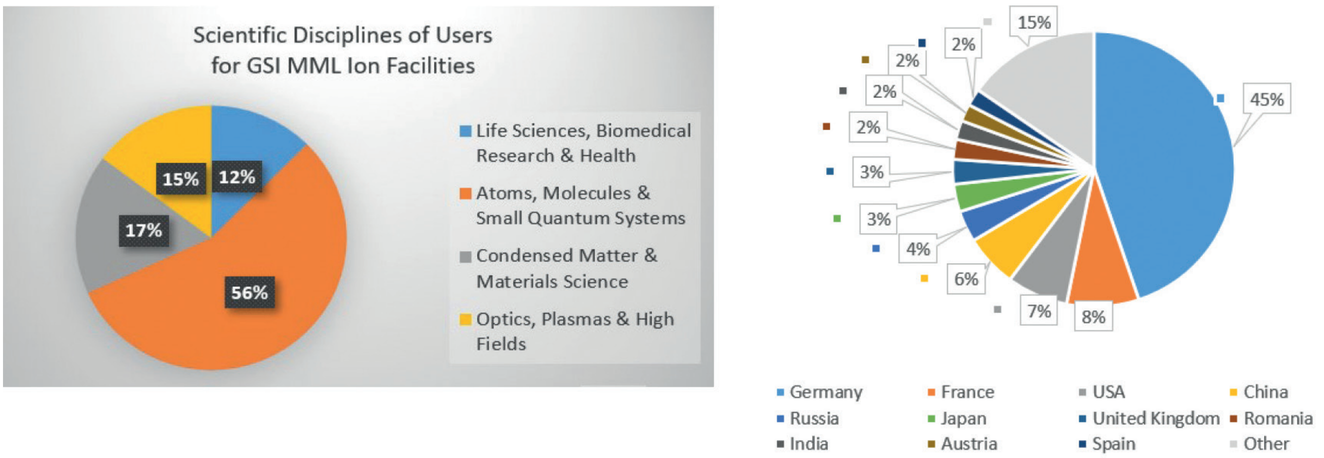

Figure 3.Scientific disciplines of users for the GSI MML ion facilities (left side) along with the user distribution by countries.

Figure 2 depicts an overview of experimental stations devoted to MML/APPA physics at GSI and the future FAIR facility whereby all the facilities on the campus of GSI (Figure 2 a) are in user operation (commissioning of HITRAP takes place in 2022). Currently, the GSI-MML facilities serve more than 450 users from national and international universi-ties and research institutes (for the user distribution with regard to the scientific disciplines and countries compare Figure 3). This user community form 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 supported by the BMBF ErUM framework program, including the research priority program APPA. GSI-MML scientists support users throughout the en-tire process, including preparation, execution and data analysis of the beam time.

2.1 Atomic physics

Head: Prof. Dr. Thomas Stöhlker (GSI, HI Jena & FSU Jena)
Authors: Angela Bräuning-Demian (GSI, FAIR), Rui Jiu Chen, Jan Glorius, Robert Grisenti (GSI, Univ.Fankfurt), Alexandre Gumberidze, Frank Herfurth, Pierre-Michel Hillenbrand, Felix Kröger (Univ. Jena), Michael Lestinsky, Robert Lötzsch (U. Jena), Esther Menz (HI Jena, GSI), Yuri Litvinov (GSI, Univ. Heidelberg), Philip Pfäfflein (HI Jena, GSI), Nikos Petridis, Stefan Schippers (Univ. Gießen), Shahab Sanjari, Uwe Spillmann, Martino Trassinelli (Sorbonne, Paris), Günter Weber (HI Jena, GSI), Danyal Winters

Figure 4. The SPARC 18th Topical Workshop took place online on September 6th-9th 2021 (in the figure, A snapshot of participants during a session is displayed). More than 170 participants from 13 countries (China, France, Germany, Greece, India, Italy, Japan, Poland, Portugal, Russia, Sweden, UK, USA) were registered and participated in the three-day online workshop. This year particular focus was on the very first experiments at the GSI/FAIR storage rings ESR and CRYRING@ESR performed within the frame of the research program FAIR Phase-0. Exciting first results from beam times in 2020/2021 have been reported.

In close cooperation with scientists from all over the world, and especially within the framework of the SPARC collaboration (see Figure 4), part of the APPA research pillar at FAIR, the working groups of the Atomic Physics Department (AP) 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. By the future HESR storage ring, the energy range will be further extended to highly relativistic energies (γ-factor up to 6), which will provide up to now unprecedented, unique research opportunities. Finally, the combination with the fragment separator (FRS) allows to extend the research spectrum to short-lived nuclides. All together, these unique and highly relevant research opportunities allow for a rich spectrum of atomic physics experiments, with the main focus on the investigation of quantum dynamics and quantum electrodynamics in extremely strong Coulomb fields as they prevail in the heaviest highly charged ions (close to Schwinger limit). In addition, atomic physics research at GSI extends to neighboring fields such as accelerator physics, materials research, plasma physics, and especially atomic and nuclear astrophysics. To reach its research goals, particular important activities of the AP division are related to the development and implementation of novel, state of the art instru-mentation (such as e.g., internal targets, lasers, x- and γ-ray polarimeters, cryogenic micro-calorimetric detectors for soft and hard x-rays, and Schottky devices). Instrumentation and detection concepts are permanently under scrutiny and optimization to enable optimal use of the above-mentioned research infrastructures.

In 2021, emphasis was given to physics production runs at the GSI/FAIR storage rings ESR and CRYRING@ESR (Swedish in-kind contribution to FAIR) by exploiting dedicated FAIR instrumentation developed by the SPARC collaboration. Note, in 2020 CRYRING@ESR has been commissioned and the ESR has been brought back into operation after a very long shutdown period. Both rings are now equipped with the FAIR control system. They are now fully operational and the storage and cooling of high-Z ions at highest charge state and secondary beams along with sophisticated beam manipulation such as deceleration are now routinely available. This is more than encouraging news for the midterm perspectives for the Atomic Physics department and the related research activities of the SPARC collaboration. These achievements were only possible due to extraordinary engagement of the various local GSI teams (e.g. ESR team, CRYRING team, technical support groups, and the members of the atomic physics depart-ment).

In the following we concentrate on the research achievements of the Atomic Physics department/ SPARC collaboration obtained within the framework of FAIR Phase-0. For further important research activities conducted at external facilities (CERN, DESY) we refer to the selected references at the end of this section. Note, for most of the research activities presented below, the Atomic Physics 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.

Highlights in 2021

FAIR Phase-0: experiments at the ESR Storage Ring

Figure 5.The ESR hevay-ion cooler and storage ring.

Despite all issues related to the COVID-19 pandemic, the Experimental Storage Ring, ESR has been successfully re-commissioned for FAIR Phase-0 experiments in 2020. For the first time the ESR has been operated with the new FAIR control system in the dedicated so-called "Storage-Ring Mode". Essential capabilities of the ESR have been re-established. Among them are beam accumulation, stochastic cooling, deceleration, event-controlled movement of detectors, operation of the internal target and many others. Many of these features could first be accomplished during the set-up time of physics experiments which sometimes caused unexpected complications.

Commissioning of the ring as well as the experimental runs continued quite successfully in 2021. Brief reports are given below. Remaining issues are in particular extraction towards HITRAP and the deceleration efficienceny which will require further commissioning and which will be addressed in the coming year. We like to especially emphasize: The overall substantial progress would not be possible without the motivated and hard work of the ESR team which we greatly appreciate.

E125: high precision tests of strong-field QED in He-like uranium

The challenging experiment E125 "High Precision Tests of Strong-Field QED in He-like Uranium" (spokesperson Martino Trassinelli, Sorbonne Université, Paris), was conducted at the internal target of the ESR storage ring, using decelerated U^{91+}, U^{90+} and U^{89+} ions. More specifically, we performed a new relative measurement of the intrashell transitions in He- and Li-like uranium with an accuracy gain with respect to a previous experiment by more than one order of magnitude. We employed a twin arm spectrometer with two bent Ge(220) crystals, both under 90° observation angle to the ion beam and equipped with X-ray CCDs. By appropriate selection of the ion velocities, the energies of the two transitions (≈ 4509 eV for He-like U and 4459.37 eV for Li-like U; see Figure 6) correspond to basically the same X-ray photon energy in the laboratory frame (4319 eV) with a drastic reduction of many systematic effects. A FWHM resolution of 2.7 eV has been obtained, mainly due to the Doppler effect coupled to the finite size of the gas jet. After several days of data acquisition, we collected more than 1000 photons per transition, allowing for a statistical accuracy of about 0.03 eV. To control the systematics of the experiment, we also measured reference lines from a stationary Zn fluorescence target as well as the intrashell transition in Be-like uranium. We aim for an accuracy of 0.2 eV on the absolute energy of the intra-shell transition in He-like uranium, mainly dictated by the accuracy of the Li-like uranium reference line, and 0.06 eV for the relative measurement of the two lines. This will allow for an unmatched test of electron correlation effects and two-loop corrections of Quantum Electrodynamics in the heaviest two-electron system. In particular, this may pave the way for a new approach for parity violation experiments at low momentum transfer for which the almost complete degeneracy between the n=2 $^1S_0$ -$^3P_0$ in He-like uranium provides favorable conditions. However, the atomic structure of this system must be explored first with utmost precision.

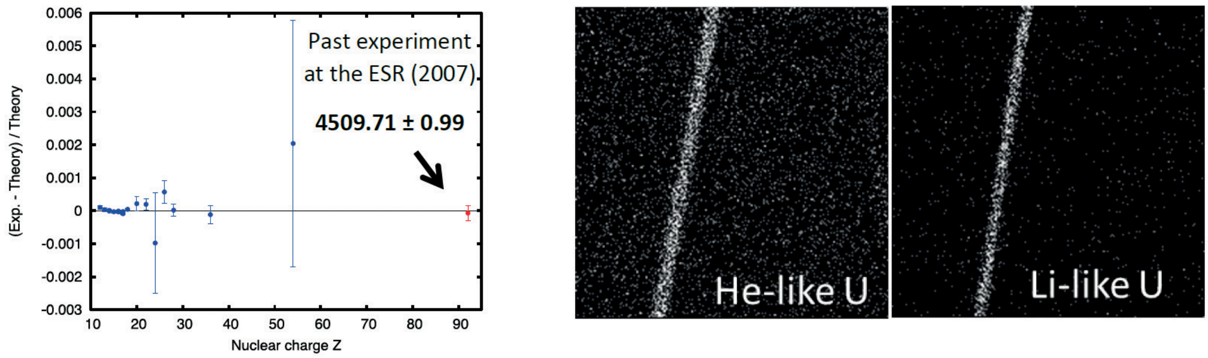

Figure 6. (Left side) Summary of available data for intrashell transitions along the isoelectronic sequence of He-like systems. The red data point results from the current experiment. (Right side) Intrashell transition in He-like U^{90+} in comparison to the corresponding transition in Li-like U^{89+} as observed in the most resent experiment in at the ESR. The observed slant of the lines is due to the relativistic Doppler effect.

E127: proton capture reactions for p-process nucleosynthesis

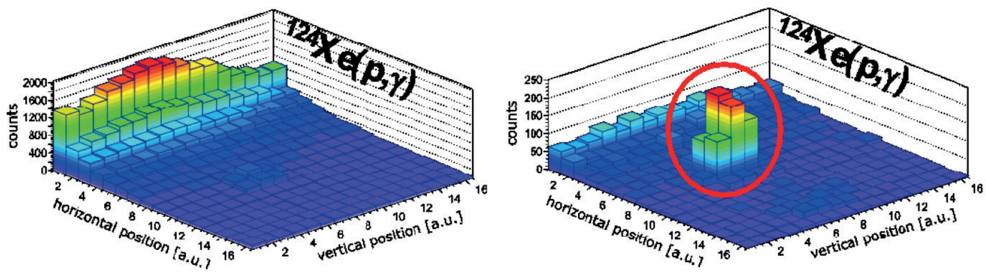

Figure 7. Distribution of hits on Double-Sided Silicon-Strip Detectors placed directly into the ultra high vacuum of the ESR inside the first dipole magnet downstream the internal jet target. Left: The spectrum is dominated by elastic scattering events of primary ^{124}Xe off the H_2 target. Right: Same as left but with elastic scattering events scraped away. The peak in the middle corresponds to ^{125}Cs ions, the products of the (p, γ) reaction of interest.

The experiment E127 has taken place at the ESR in spring 2021 successfully utilizing radioactive beams for the first time. This success was only possible due to previous thorough commissioning studies using stable beams. Proton capture reaction on stable ^{124}Xe in the center-of-mass energy range from 6 to 8 MeV/u has been measured [1]. The lowest energy is just at the upper edge of the Gamow window of the p-process of stellar explosive nucleosynthesis. Since then, the sensitivity of the experiment has been dramatically boosted by physically removing the background due to elastic scattering. This is illustrated in the Figure 7.

This new technique was termed "ERASE" [2] and is a subject of the PhD thesis of Laszlo Varga, successfully defended at the University of Heidelberg in July 2021. Owing to this technique, the proton capture reaction on a low-intensity radioactive beam stored at an energy as low as 6 MeV/u could be conducted. The chosen beam was ^{118}Te. The measured distribution of ions hitting the employed double-sided silicon-strip detectors installed in the first dipole of the ESR downstream the H_2 internal gas target is illustrated in the figure. This result is a milestone step forward to perform reaction studies on radioactive ions directly in the Gamow window of the p-process planned at the ESR as well as at CRYRING@ESR.

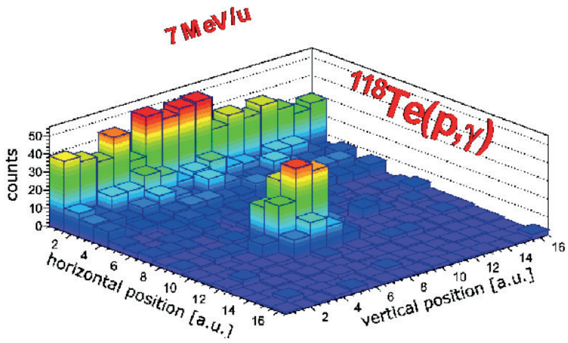

Figure 8. Same as the Figure 7 but for the case of the radioactive ^{118}Te ions. The peak in the middle corresponds to 119I ions, the products of the (p,γ) reaction of interest.

- [1] J. Glorius et al., Phys. Rev. Lett. 122 (2019) 092701
- [2] L. Varga, PhD thesis, University Heidelberg, July 2021

GSI "beam experiment" for laser cooling of bunched relativistic ion beams

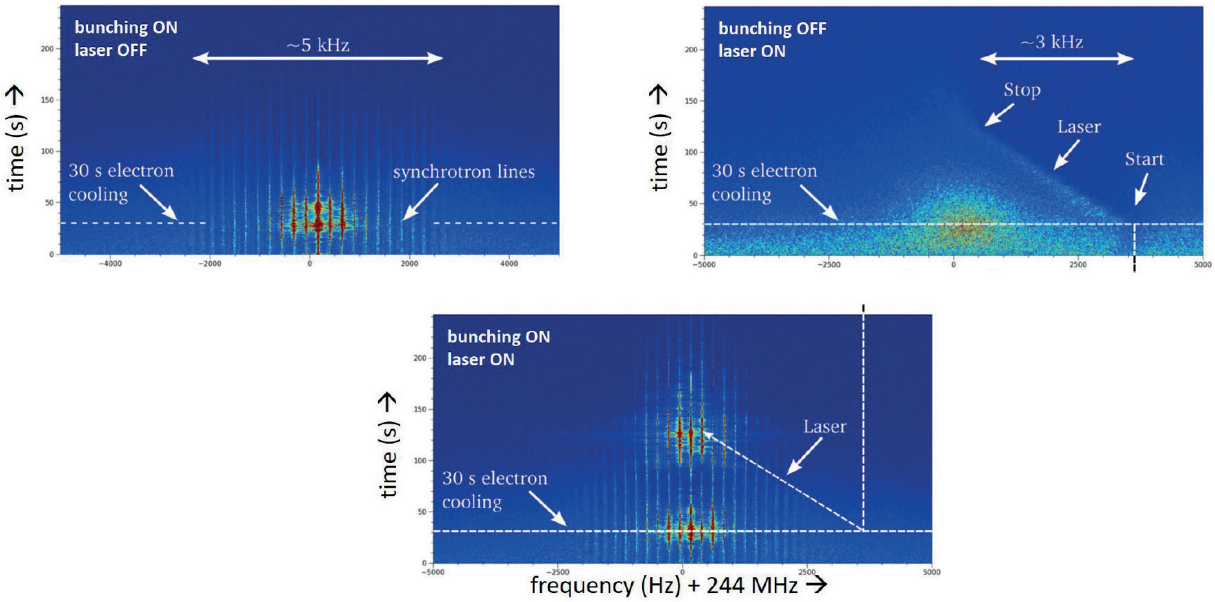

Figure 9. Schottky spectra related to laser cooling of C^{3+} ions at the ESR.

In May 2021, we performed a "beam experiment" for laser cooling studies at the ESR, using Li-like carbon ions at 122 MeV/u ($^{12}C^{3+}$ @ β=0.47). The study was a proof-of-principle for the broadband laser cooling using a new tunable pulsed UV laser system. In parallel the improved moveable Extreme Ultra-Violett XUV detector system developed by a group at Münster University was tested by measuring the ions' fluorescence. Another important study was focused on the "ion bunch – laser pulse timing" which was done by delaying the laser pulses with respect to the ion bunches. The pulsed laser system developed at the TU Darmstadt, has a very high repetition rate (up to 10 MHz), a variable pulse duration (from 166 to 740 ps), adjustable central wavelength (~257 nm) and significant power (~200 mW). The improvements of the XUV detector implies a very precise positioning close to the stored ion beam trajectory (by a stepper motor) and a better shielding.

We could, for the first time, demonstrate laser cooling using the tunable high repetition rate laser system. The Figure 9 shows three Schottky "images" recorded at the ESR. The upper left panel shows a bunched ion beam without laser, the upper right panel a coasting ion beam with a scanning laser, and the bottom panel the scanning laser and a bunched ion beam. The latter shows the true laser cooling. We could also uniquely demonstrate the interaction of broadband laser pulses - of different durations - with the stored ion beam.

FAIR Phase-0 experiments at CRYRING@ESR

Figure 10. CRYRING@ESR.

During 2020, CRYRING@ESR has seen significant progress on its path to routine operation as a user facility. Incremental upgrades in particular to the vacuum are still ongoing, but all machine subsystems are now in operation and ready for all approved G-PAC proposals. Despite the pandemic and the resulting cancellation of scheduled experiments, a test beam period during spring was performed to demonstrate the potential of the facility and we were able to test the first experimental systems under realistic beam condition. Remote operation of the machine and the experiments has been established, so that only minimal physical presence of operators and scientists will be needed in the future. Storage and cooling of highly charged ions delivered from ESR was demonstrated [1], and the observed lifetimes of the beams of highly charged ions (Pb^{79+} and Pb^{82+}) lie within the predicted range. In 2021, the exloration of the unqiue capabilities for research with highly charged ions continued and were demonstrated by two flagship experiments using Pb^{78+} and U^{91+} ion beams provided by the ESR (see below).

Independent operation of CRYRING with beams delivered through a local injector beamline was improved in 2020 with the implementation of a compact ECR-type source contributed by colleagues from University of Giessen and adapted to the HV ion source terminal of the injector and integrated to the FAIR-type control system. In 2021, the physics potential of this installtion was impressively demonstrated by various experiments such as for studies of low-energy DR for Ne^{2+} relevant for modelling of cold, photoionized plasmas, or planetary nebulae.

For the beamtime period of 2021 and 2022, G-PAC has approved 10 experiment proposals at CRYRING, with four resubmissions from the last G-PAC period and six new proposals. Out of these, three require beam from ESR, and seven will use the local injector. Six experiments have received A rating and four A-. Finally, we note that for an experiment in the realm of material research Ag^{47+} were injected into CRYRING@ESR, further decelerated to 5.9 MeV/u and extracted to irradiate polymer foils at the MAT station at CRYRING. This constitutes a further important milestone for the commissioning of CRYRING@ESR.

Beams stored in 2020: d^{+}, Mg^{+}, Pb^{78+}, Pb^{82+}, Ne^{7+}, Ne^{3+}, Ne^{4+}

Beams stored in 2021: Mg^{+}, O^{6+}, N^{2+}, Ne^{3+}, Ag^{47+}, Pb^{78+}, U^{91+}

- [1] B. Zhu et al., arXiv:2201.06977 (2022)

E131: precision collision spectroscopy of $^{208}Pb^{78+}$ at CRYRING@ESR

For the experiment E131 Precision Collision Spectroscopy of $^{208}Pb^{78+}$ (S. Schippers et al.), Be-like lead ions were decelerated in the ESR to the extraction energy of 11 MeV/u and injected into the CRYRING@ESR. A transfer efficiency close to 50% has been achieved, allowing to store up to $5x10^{6}$ particles at CRYRING resulting in an effective particle intensity of $4x10^{11}$ ions/s with a beam lifetime of close to 30 s. At CRYING@ESR, the ions were first cooled using the ultra-cold electron beam of the CRYRING electron cooler. Thereafter, di-electronic resonances were studied by fast scanning of the electron beam energy (cooler voltage) over the resonance regime and by observing the recombination of the cooler electrons via measuring the down-charged $^{208}Pb^{77+}$ using a particle detector located downstream of the cooler section behind a dipole magnet. A preliminary sample spectrum obtained is displayed in the Figure 11 where a prominent di-electronic resonance structure is clearly visible. This result already demonstrates that collision spectroscopy at the CRYRING cooler can be carried out with a substantially higher resolving power as compared to previous experiments at the ESR. In addition, it became apparent that there is still room for improvement. In particular, this concerns the vacuum conditions in CRYRING where the background from electron capture from the residual gas limits our statistics. For the detailed benchmarking of theory, a detailed data analysis is in progress.

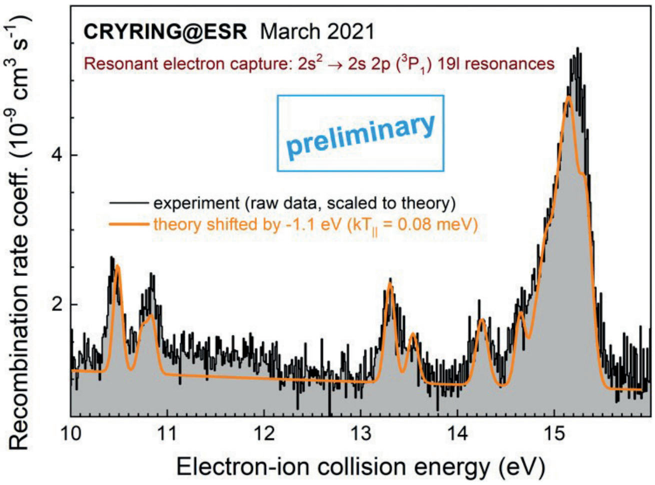

Figure 11. Preliminary di-electronic recombination spectrum for collisions of Pb^{78+} ions with ultra-cold electrons at the CRYRING@ESR electron cooler.

E138: 1s Lamb-shift in H-uranium

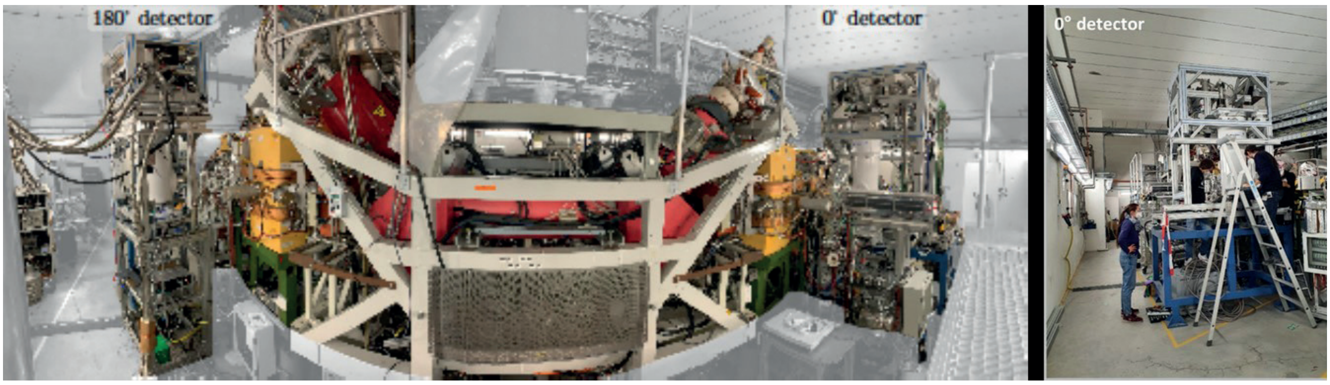

Figure 12. Implementation of a novel high-resolution, cryogenic μ-calorimeters each equipped with a 64 pixel area. In the figure, one of the two γ-calorimeters is displayed at its final position at the 0 deg port at the CRYRING@ ESR electron cooler (upper part).

A very challenging experimental enterprise was started within the framework of E138, 1s Lamb Shift in H-like uranium (test of non-perturbative QED on the 1 eV level (spokesperson Günter Weber, HI-Jena). Due to the overall boundary conditions, the experiment focused in a first step on the ground-state transition in He-like ions in order to train the requires beam manipulations along the complex experimental setup. For the experiment H-like U^{91+} ions were injected at 300 MeV/u into the ESR and electron cooled at the ESR. Thereafter the ions were decelerated to 10 MeV/u and injected into the CRYRING@ESR. At CRYRING@ESR, the ions were electron cooled again and the x-ray emission mediated by radiative recombination of electrons in the cooler section was detected by cryogenic microcalorimeter detectors in coincidence with down-charged U^{90+} ions (see Figure 13 below). The two micro-calorimeter detectors installed, had been developed during recent years within the framework of the SPARC collaboration (so called maXs detectors'; magnetic microcalorimeter detectors). With an operation temperature between 30 and 70 mK, these detectors provide an excellent energy resolution comparable to Bragg crystal spectrometers but basically without any wavelength restriction. Due to several issues related to beam handling along the long transfer chain involving UNILAC, SIS18, and ESR, only about 30% of the beam time could be efficiently used. However, it could already be demonstrated that currently $2x10^6$ H-like uranium ions can be stored at CRYRING@ESR. This amounts to an improvement of intensity by a factor of 5 compared to the commissioning run one year ago with bare Pb^{82+} ions [1]. Further progress can be anticipated such as the vacuum conditions at ESR and CRYRING@ESR as well as the beam transfer efficiency between both rings.

Despite the statistical limitations, the collected data already allowed to observe the splitting of the $K\alpha_2$ into subcomponents for an element with nuclear charge Z>54 for the first time (ee Figure 13). This demonstrates the excellent resolving power of the detectors applied. Moreover, while previous test measurements with microcalorimeters at the accelerator facility of GSI were conducted in the mode of well-established stand-alone operation, for the present experiment we implemented several notable modifications to exploit the full potential of this type of detectors. Among these are a new readout system compatible with the multibranch system data acquisition platform of GSI, the synchronization of a quasi-continuous energy calibration with the operation cycle of the accelerator facility, as well as the first exploitation of the maXs detectors' time resolution to apply coincidence conditions for the detection of photons and charge-changed ions [2].

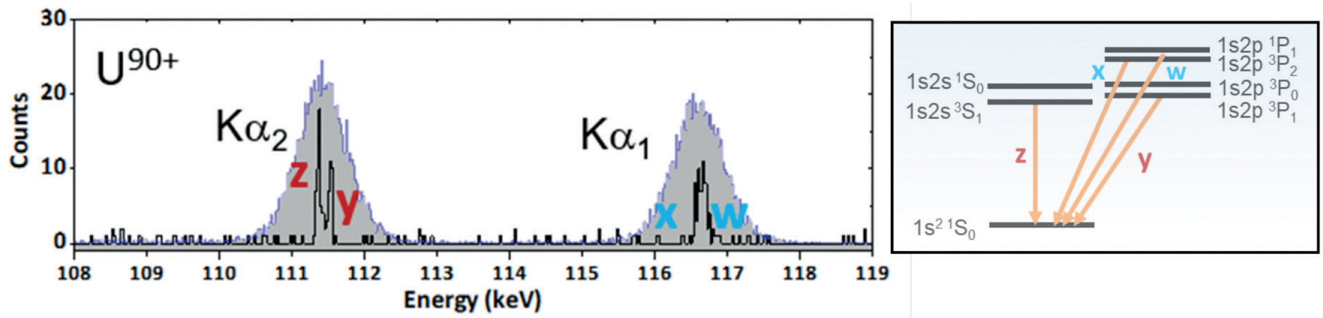

Figure 13. In the lower part of the figure, the energy regime of the Kα lines of He-like U^{90+} is displayed (preliminary spectrum). Most important a line splitting into z and y component is observed for the Kα2 line in an element of nuclear charge Z>54 for the first time (see left lower part of the figure), demonstrating the excellent resolution power of the detectors applied.

Currently, the collected data are subject of detailed investigations.

- [1] B. Zhu et al., arXiv:2201.06977 (2022)
- [2] Ph. Pfäfflein et al., arXiv:2202.00319 (2022)

Outlook for 2022 and beyond

In 2022, user operation at ESR and CRYRING@ESR will continue with the goal reaching the design parameters. Beside challenging experiments such as di-electronic-recombination-assisted laser spectroscopy and studies of the excitation and decay properties of ^{229}Th (nuclear clock), special emphasis will be given to the re-commissioning of HITRAP. For 2023, we expect to have the full storage and trapping facility complex including HITRAP available for production runs.

Selected publications of 2021

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- [2] Bohman, M. ; Grunhofer, V. ; Smorra, C. ; et al.: Sympathetic cooling of a trapped proton mediated by an LC circuit. Nature <London> 596(7873), 514 - 518 (2021), DOI:10.1038/s41586-021-03784-w
- [3] Nörtershäuser, W. ; Surzhykov, A. ; Sanchez Alarcon, R. M. ; et al.: Polarization-dependent disappearance of a resonance signal: Indication for optical pumping in a storage ring? Physical review accelerators and beams 24(2), 024701 (2021), DOI:10.1103/PhysRevAccelBeams.24.024701
- [4] Hillenbrand, P.-M. ; Lyashchenko, K. N. ; Hagmann, S. ; et al.: Electron-loss-to-continuum cusp in collisions of U89+ with N2 and Xe. Physical review / A 104(1), 012809 (2021), DOI:10.1103/PhysRevA.104.012809
- [5] Yamaguchi, T. ; Koura, H. ; Litvinov, Y. ; et al.: Masses of exotic nuclei. Progress in particle and nuclear physics 120, 103882 (2021), DOI:10.1016/j.ppnp.2021.103882
- [6] Heylen, H. ; Devlin, C. S. ; Gins, W. ; et al.: High-resolution laser spectroscopy of $^{27-32}$Al. Physical review / C 103(1), 014318 (2021), DOI:10.1103/PhysRevC.103.014318

2.2 Materials research

Head: Prof. Dr. Christina Trautmann (TU Darmstadt & GSI)
Authors: Christina Trautmann, Maik Lang (Univ. of Tennessee, Knoxville), Eugenia Toimil-Molares

During the beamtime block in 2021, the operation of the materials science user platform was challenging, but despite the pandemic, about 80% of the scheduled irradiation experiments for ~40 different user groups were successfully completed. In Cave A (SIS18), the setup for irradiating samples pressurized in diamond anvil cells (DAC) was complemented by a Raman spectrometer for online monitoring phase changes under extreme pressure and irradiation conditions. At the CRYRING, the irradiation chamber at the new beamline with extracted beam was commissioned and the first samples were irradiated with fully stripped 5.9 MeV/u Ag ions. The installation comprises a UHV chamber with a load lock system for sample exchange and various analysis techniques to be integrated. The scientific aim is to study ion-solid interaction and nanostructuring processes with ions of highest charge states and variable kinetic energy between 0.1 and 10 MeV/u. At the M-branch (UNILAC), the existing analytical techniques for monitoring beam-induced effects in solids was complemented by in situ Raman spectroscopy. Several users investigated fragmentation of complex organic molecules to simulate astrochemical processes in space. Investigations of functional materials for application in accelerators focussed on the outgassing of vacuum components and on dynamic effects induced by short-pulsed beams in graphite targets. Results from irradiation experiments with pulsed protons at CERN and with heavy ions at the GSI UNILAC combined with laser Doppler vibrometry have now been published [1]. At the beamline X0 (UNILAC), a large variety of low and high fluence irradiations for radiation damage studies and for ion-track based nanotechnology projects were performed (examples in [2-6]). At the heavy ion microprobe several groups tested electronic devices for space applications.

Highlights in 2021

A new sensor for SARS-CoV-2 and other viruses based on ion-track nanotechnology

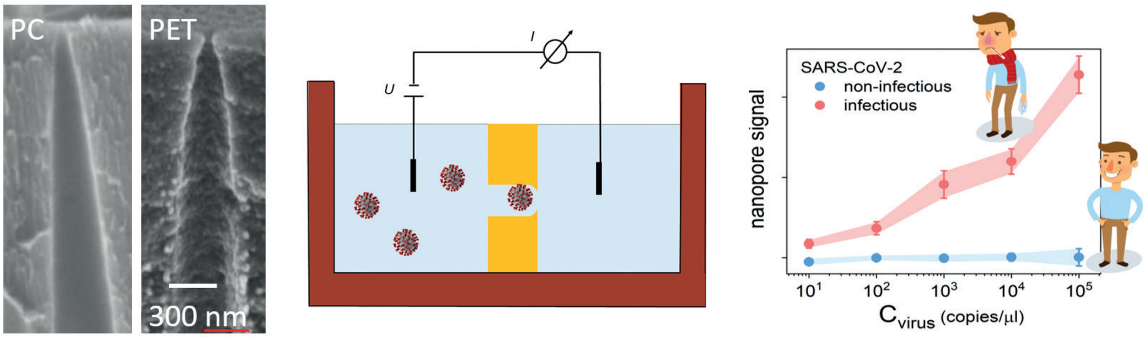

Figure 14. (left) Scanning electron micrographs of cross sections of asymmetric nanochannels in ~10 µm thick polycarbonate.

Based on single-nanopore membranes of GSI, an international interdisciplinary team has developed a nanopore-based sensor that can detect and distinguish infectious from non-infectious corona viruses. The sensor combines two key components: a sensitive nanochannel (GSI Materials Research) and highly specific DNA molecules attached to the channel surface (National Scientific and Technical Research Council (CONICET) in Argentina and the University of Illinois in the USA). The technology for the fabrication of membranes with single nanopores has been developed at GSI over many years. Thin polymer films are irradiated with one individual high-energy heavy ion that creates a nanoscopic damage trail. Chemical etching converts this track into an open nanochannel. For the sensor, asymmetric nanopores with a small opening of less than 50 nm were fabricated and subsequently coated with DNA aptamers that were selected from a DNA library to bind the intact infectious, but not the non-infectious virus. The high sensitivity and specificity of the sensor were demonstrated via I-V ion transport measurements through the open or virus-clogged nanochannel using a conductivity cell [2]. Applications of the aptamer-nanopore sensors in different types of water samples, saliva, and serum were confirmed for both enveloped and non-enveloped viruses, making the sensor generally applicable for detecting SARS-COV or other emerging viruses.

Conical nanotubes synthesized by atomic layer deposition in etched ion-track nanochannels

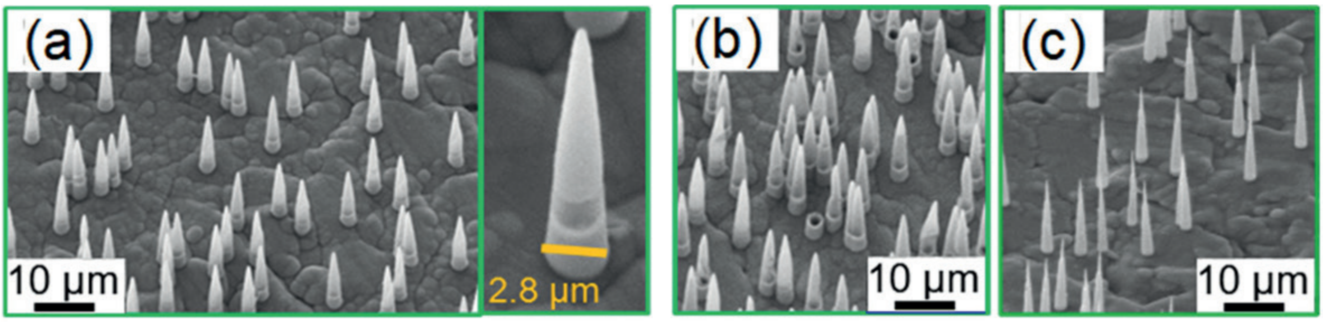

Figure 15. Scanning electron micrographs of 30 µm long, free standing, conical TiO_2 nanotubes with a wall thickness of (a) 20 nm, (b) 15 nm, and (c) 10 nm [3].

Surface coating by atomic layer deposition (ALD) has the potential to significantly widen the technological and scientific applications of ion-track etched membranes with highly oriented, monodisperse nanochannels. ALD provides conformal surface coating with well controlled layer thickness and chemistry. Conformal ALD coating with TiO_2, SiO2, and Al_2O_3 has been successfully demonstrated for cylindrical and conical nanochannels in track-etched polycarbonate membranes with aspect ratios (length to diameter) up to 3000. By subsequent removal the membrane material, arrays of nanotubes with wall thicknesses between ~10 and ~20 nm were fabricated (examples of conical nanotubes in Figure 15). The mechanical stability of the free-standing nanocones depends on both the material and thickness of the deposited wall [3].

The ALD technology in combination with track-etched membranes provides interesting hybrid systems and offers new perspectives for the tailoring of nanofluidic systems. The coating process can be used to controllably reduce the diameter of the tip of a conical nanopore and to tailor the surface chemistry and charge of the channel wall by selecting a specific coating material. The ALD coating with, e.g., TiO_2, SiO2, or Al_2O3 creates an inorganic surface with a defined isoelectric point and offers a novel basis for surface functionalization for ion transport systems. The coating maintains the flexible character of the membrane and increases the long-term stability of the system.

Multi-scale structural response of pyrochlore compounds to swift heavy ion irradiation

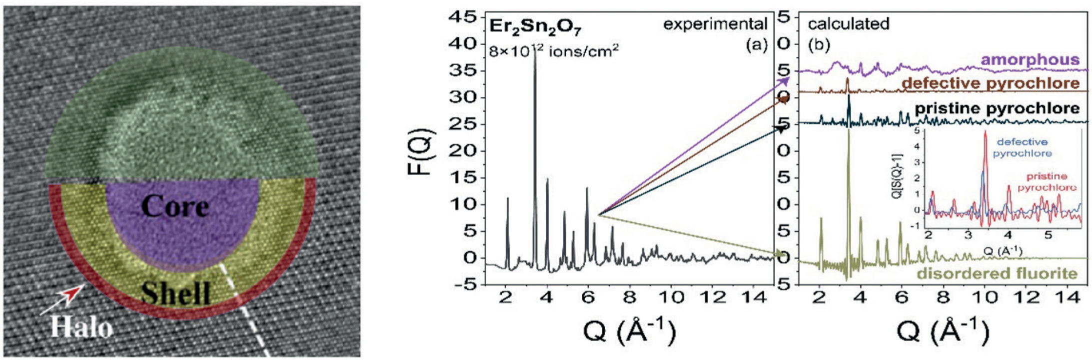

Figure 16. (Left) TEM image of a single track in pyrochlore with the amorphous track core (purple) surrounded by a disordered, anion-deficient fluorite shell (yellow) and a defective pyrochlore halo (red) according to the long-range and intermediate-range neutron analysis. PDF data analysis evidences a homogeneous weberite-type short-range structure indicated by the transparent green region. (Right) Reduced neutron structure functions (a) experimental data and (b) simulations from Fourier transform of the individual crystalline phases (pristine pyrochlore, defective pyrochlore, and disordered fluorite) derived from intermediate-range structure refinement of the PDF [4].

Complex oxide materials that adopt the pyrochlore structure ($A_2B_2O_7$ stoichiometry) exhibit a wide variety of exotic properties such as giant magnetoresistance, oxygen ion conductivity, and superconductivity. Due to their exceptional radiation stability, pyrochlore oxides have been proposed as durable matrices for the incorporation and immobilization of nuclear wastes. The relative size of ion-induced damage zones and the final structural response to high fluences are primarily governed by the chemical composition of the pyrochlore compound. In this project, the phase evolution and track morphology of $Er_2Sn_2O_7$ irradiated with of 2.2 GeV Au ions was comprehensively analyzed by transmission electron microscopy (TEM), X-ray diffraction (XRD), and neutron total scattering with pair distribution function (PDF) analysis. Each technique probes different aspects and length scales of the transformed material regions. TEM revealed a core-shell structure of the ion track with an amorphous core surrounded by a disordered, anion-deficient fluorite shell, which was confirmed by XRD. In contrast to TEM and XRD, neutron total scattering has the advantage of being sensitive to the oxygen sublattice and providing relative fractions of amorphous and disordered fluorite phases. The neutron data confirmed the presence of an amorphous core and a disordered fluorite shell, but additionally revealed a defective pyrochlore phase, which largely maintains its structural ordering but is clearly distinct from the pristine pyrochlore matrix. This defect-rich pyrochlore phase forms a halo extending radially beyond the well-characterized core-shell track morphology observed by TEM. While the intermediate- and long-range structural analysis revealed a heterogeneous track structure with three distinct damage zones, characterization of the short-range structure by neutron PDF analysis provided a distinctly different picture. Tracks are fully homogeneous over the short-range structure with only weberite-type atomic arrangement from the inner core to the outer halo region. The length-scale over which damage is probed is obviously an important component to be considered in defining the radiation tolerance of a given material [4].

Outlook for 2022

In beamtime block 2022, FAIR Phase-0 activities will continue at all MAT-operated beamlines. The high-pressure platform in Cave A will be improved by high-precision positioning systems for the beam collimators, DAC stage and Raman spectrometer. The installation of an in-situ confocal UHV-Raman spectrometer is planned at the MAT target station of the CRYRING.

The department is involved in cross-center Helmholtz Innovationpool projects MaDQuanT (Materials Dynamics for Future Quantum Technologies) and FISCOV as well as in the highly interdisciplinary project CORAERO. The research objectives of the latter two initiatives deal with SARS Corona virus topics.

Selected publications of 2021

- [1] Simon, P. ; Drechsel, P. ; Katrik, P. ; et al.: Dynamic Response of Graphitic Targets with Tantalum Cores Impacted by Pulsed 440-GeV Proton Beams. Shock and vibration 2021, 1 - 19 (2021), DOI:10.1155/2021/8884447
- [2] Peinetti, A. S. ; Lake, R. J. ; Cong, W. ; et al.: Direct detection of human adenovirus or SARS-CoV-2 with ability to inform infectivity using DNA aptamer-nanopore sensors. Science advances 7(39), eabh2848 (2021), DOI:10.1126/sciadv.abh2848
- [3] Ulrich, N. M. ; Spende, A. ; Burr, L. ; et al: Conical Nanotubes Synthesized by Atomic Layer Deposition of Al_2O_3, TiO_2, and SiO_2 in Etched Ion-Track Nanochannels. Nanomaterials 11(8), 1874 (2021), DOI:10.3390/nano11081874
- [4] O'Quinn, E. C. ; Tracy, C. L. ; Cureton, W. F. ; et al.: Multi-scale investigation of heterogeneous swift heavy ion tracks in stannate pyrochlore. Journal of materials chemistry / A 9(31), 16982 - 16997 (2021), DOI:10.1039/D1TA04924K
- [5] Länger, C. ; Ernst, P. ; Bender, M. ; et al.: Single-ion induced surface modifications on hydrogen-covered Si(001) surfaces—significant difference between slow highly charged and swift heavy ions. New journal of physics 23(9), 093037 (2021), DOI:10.1088/1367-2630/ac254d
- [6] Kiy, A. ; Notthoff, C. ; Dutt, S. ; et al.: Ion track etching of polycarbonate membranes monitored by in situ small angle X-ray scattering. Physical chemistry, chemical physics 23(26), 14231 - 14241 (2021), DOI:10.1039/D1CP02063C

2.3 Plasma physics

Head: Priv. Doz. Dr. Vincent Bagnoud, GSI
Author/s: Thomas Campbell (Oxford U.), Stefan Götte, Johannes Hornung (HI Jena, GSI), Martin Metternich (TU Darmstadt), Haress Nazary (TU Darmstadt), Paul Neumayer (U. Frankfurt/M, GSI), Olga Rosmej (U. Frankfurt/M, GSI), Dmitry Varentsov

During the considered reporting period, the plasma physics department at GSI has focused on the re-start and upgrade of the experimental capabilities at the high-energy high-temperature cave (HHT) at the extraction of the SIS18 synchrotron, while maintaining its commitment to operation at the target station PHELIX and Z6. Altogether, these caves with their technical characteristics represent worldwide unique experimental areas for experiments in the realm of high-energy-density physics (HEDP) and applications [1].

At the beginning of 2021, the plasma physics department rode along the beam time of GSI's accelerator facilities to conduct a series of experiments and technical developments, as described below in the "Highlights" section. During this time, the COVID-19 pandemic affected our work, because several disease waves coincided with beam times, which restricted the work environment at GSI and travel of users to Germany. In February, the PRIOR-II proton microscope for FAIR came into operation successfully, while we commissioned the laser beam line connecting PHELIX to HHT in May. This new developments are major milestones to support the scientific program of the HED@FAIR collaboration at the upcoming FAIR facility (see highlights).

In parallel, full operation kept going on at the PHELIX laser supporting eleven experimental campaigns throughout the year. Most of these experiments took place at the PHELIX petawatt area, while the experimental area Z6 in the experiment hall of GSI hosted two beam times. In particular, an experiment aiming at explaining the generation of hyper-relativistic particles in the universe via scattering in plasma was conducted using the combination of a laser-generated plasma driven by PHELIX and well-defined ion bunches from the accelerator (see highlights). Because of the COVID situation in the country of origin of the experimental group, a fully staff-assisted beam time had to be organized on short notice to cope with travel restrictions and to support this long-standing experimental campaign, avoiding therefore further planning delays in the conduction of this challenging beam time.

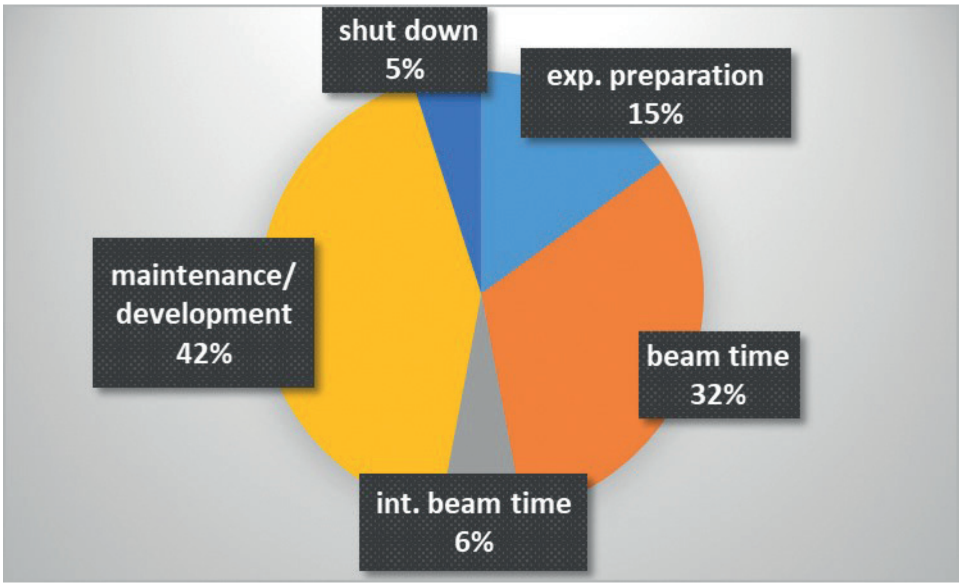

Figure 17. Usage of PHELIX in 2021.

Overall, the year turned out nearly normal from an operational point of view, with 57% of the year dedicated to experiments (long-term average at 63%) and a 9-week maintenance block in fall dedicated to the upgrade of the short-pulse front end in the framework of the ATHENA project (see Figure 17). In general, to make beam time possible in 2021, a strong involvement of the department staff was necessary to allow users to drive the experiments remotely. In addition, at the peak of the pandemic-related restrictions, extended shifts and additional time was devoted to operation to cope with the severe work place occupancy restrictions. As a result, projects with lower priority had to be delayed to free up the necessary resources.

Other projects in the department dealt with, for example, laser beam quality [2] or the third-party-funded ATHENA program, which inscribes itself in the Helmholtz-Association-wide effort to promote plasma-based accelerators. Here, one working package deals with the development of temporally-clean millijoule-level short pulses for Petawatt lasers. After successful validation of our new concept at PHELIX and a gradual increase of the performance in 2021, we build a replica of this system for the PENELOPE laser at the Helmholtz Center Dresden-Rossendorf. System delivery and installation should follow in 2022.

The beam time in the plasma physics caves, as for all other experimental areas at GSI, is decided by GSI's director, based on the recommendations of advisory committees. In 2021, the Plasma Physics Advisory Committee met in December to make recommendations on experiment proposals using PHELIX for the period extending from summer 2022 to summer 2023. This was the opportunity to reassess of the attractiveness of the facility.

Highlights in 2021

Commissioning and first experiment with PRIOR II

High-energy proton microscopy (HEPM) is regarded as a key diagnostic for HEDP experiments with intense heavy ion and proton beams, which are planned at GSI/FAIR by the HED@FAIR collaboration. In February 2021, the commissioning of a new worldwide-unique HEPM facility called PRIOR-II (Proton Microscope for FAIR) took place successfully at the HHT experimental area with proton beams from SIS18. The new facility employs small but strong and radiation-resistant normal-conducting electromagnets designed and constructed for HED@FAIR experiments.

The beam time commissioning of the PRIOR-II facility with 2 GeV and 4 GeV protons, which has been performed in a collaboration between GSI-Darmstadt, TU-Darmstadt, GU-Frankfurt, LANL-Los Alamos, ITEP-Moscow and IPCP-Chernogolovka, has demonstrated its remarkable radiographic capabilities, not only the enhanced contrast and great spatial resolution of about 15 µm but also a significant increase in the field of view. The dynamic physics experiments with PRIOR-II were the occasion to study underwater electrical wire explosions with an exceptional 5-20 ns temporal resolution. The obtained results have confirmed that the new PRIOR facility, which employs high-energy proton beams delivered by the GSI/FAIR synchrotrons, will provide a significant step forward to ad-vance materials research and dense plasma physics.

Development and test of the HIHEX setup at HHT

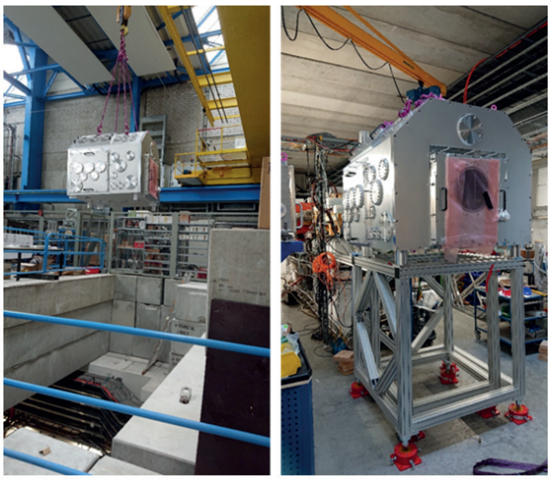

Figure 18. Installation of the new APPA target chamber at the HHT-cave.

Rapid heating by intense heavy-ion pulses from the SIS100 will be among the core techniques utilized by the HED@ FAIR collaboration to create matter states at extreme conditions. The delivery of the target chamber for day-1 experiments in the APPA cave, developed in collaboration with the JWGU Frankfurt, took place in April 2021 and it passed the final acceptance test at GSI (see Figure 18). In the FAIR Phase-0, the necessary development of diagnostic methods and validation of experimental schemes will be carried out at the HHT-cave, where pulses from the SIS18 can be focused to millimeter spot sizes. To this end, our group installed the new target chamber at the HHT-cave, allowing first proof-of-principle experiments. In a commissioning beam time carried out in spring, heavy ion-pulses from the

SIS18 with up to 3×10⁹ Xe ions per bunch, focused inside the new target chamber, created a focal spot distribution of about 1 mm in diameter. Optical imaging of both the beam-induced fluorescence in a few mbar Argon gas fill and the optical transition radiation from thin foil targets corroborated this information. At the focus position, the temperature distribution of a heavy-ion heated tungsten target was measured by means of a newly developed 2-channel gated pyrometer.

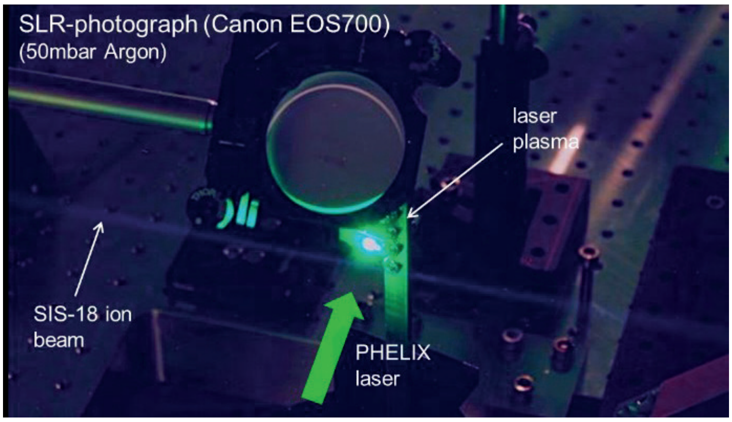

Figure 19. Intense heavy-ion pulse and high-energy laser beam simultaneously focused in the new target chamber.

A major achievement enabling FAIR Phase-0 research has been the completion of the 2-year project to construct a 70-m-long laser beamline, transporting high-energy laser pulses from the PHELIX facility to the HHT-cave. This will allow driving powerful x-ray sources to probe the dense matter states created with heavy-ion beams. The commissioning of the beamline took place in June. Excellent beam-pointing stability was shown and focusing of the laser to 50 µm spot sizes could be achieved. Laser pulses with energies in excess of 100 J were delivered to the HHT-cave, and synchronization with the accelerator timing system to less than 10 ns was demonstrated. Together with external research groups from the HED@FAIR collaboration the laser pulses were successfully used to gener-ate intense x-ray pulses from laser-driven plasmas, reaching conversion efficiencies of the order of 10^{-3} from laser energy to multi-keV x-ray line emission. This type of x-ray sources is widely used at state-of-the-art HED facilities worldwide to enable advanced diagnostics of extreme matter states. In our experiment, we have successfully demonstrated both x-ray diffraction and x-ray Thomson scattering, two powerful x-ray probing techniques revealing microscopic properties of dense plasmas. This is in preparation for the first combined experiments using both heavy-ion and high-energy laser pulses at HHT in the beamtime block in 2022. These provide a milestone towards the APPA-cave, where heavy-ion pulses with 1-2 orders of magnitude higher particle numbers will be available from SIS18 and SIS100, and a newly developed laser-system will provide x-ray diagnostics capabilities for HED science experiments.

Analytical description of laser-driven holeboring into an arbitrary plasma density profile

In many laser-driven ion acceleration experiments conducted at PHELIX, the properties of the dense plasma de-veloping during the last instant prior to the arrival of the peak laser irradiation is critical for the outcome of the ac-celeration process. During such an interaction, the spectral properties of the reflected laser pulse, modulated by Doppler-broadening due to the laser-holeboring process, can deliver insight into the interaction process itself. We therefore developed an analytical model, which describes the temporal evolution of holeboring, using realistic plasma density and laser intensity profiles. This extends the standard equation for the holeboring velocity by considering a temporally varying electron density n, described by the so-called plasma density scale length $L_c = n_c / \nabla n_c$ of the profile, with a density gradient ∇n_c at the critical density n_c, which results in:

$$v_{HB}(t) = \frac{2L_c\sqrt{I(t)}}{\int_{-\infty}^{t}\sqrt{I(\tau)d\tau} + 2L_c\sqrt{\frac{cn_cM_i}{Zcos(\theta)}}}$$

Here, c describes the speed of light, n_c the critical plasma density, M_i and Z the mass and charge state of the ions and ϑ the incidence angle between laser and target. Therefore, the holeboring velocity reduces in the presence of a shorter scale length. This behavior and therefore the analytical description has been confirmed by performing 2-D Particle-In-Cell (PIC) simulations, showing a very good agreement quantitatively. Comparing experimental measurements of the spectral shift, introduced by the moving reflective surface, with the analytically predicted spectral shift additionally enables indirectly measuring the gradient of the plasma in experimental conditions. Such a measurement is especially challenging for short scale lengths in the sub-micrometer regime. Therefore, monitoring the reflected laser pulse can help to enhance the understanding about the plasma conditions and therefore the laser-plasma interaction itself [3].

Simulation in the laboratory of the scattering of ultra-relativistic particles within astrophysical plasma clouds: a diffusive ion acceleration experiment

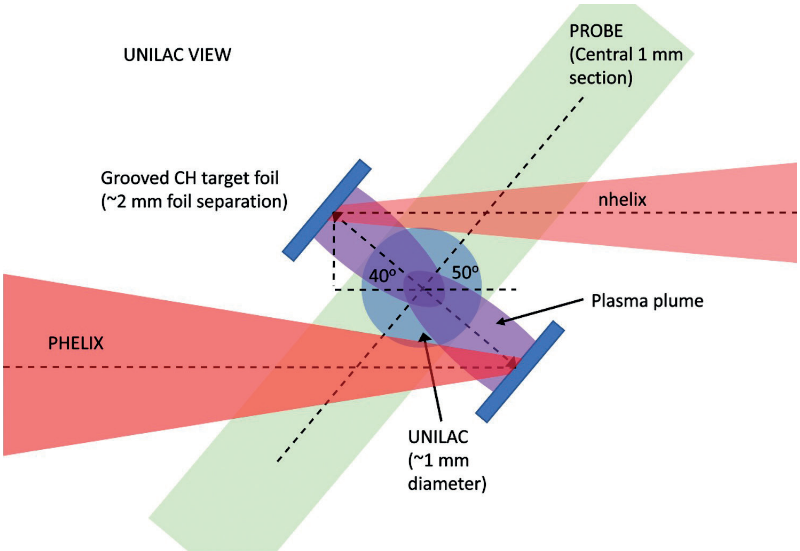

Figure 20. Experimental Setup.

The exact mechanism that enables the acceleration of highly energetic charged particles in the Universe, cosmic rays, CR, remains controversial. Although many processes may result in cosmic ray acceleration, turbulence is generally accepted to be essential to energizing the ions and electrons in the interstellar medium. Indeed, the original mechanism of CR acceleration proposed by Fermi [E. Fermi (1949) Physical Review 75] theorised that energetic charged particles gain energy in random scattering events with magnetized clouds. Given that the standard model for the origin of these magnetic fields is via the turbulent dynamo mechanism [F. Miniati (2015) Nature 523], it is clear that the key process governing CR acceleration is related to how charged particles interact with stochastic magnetic fields embedded in a turbulent plasma.

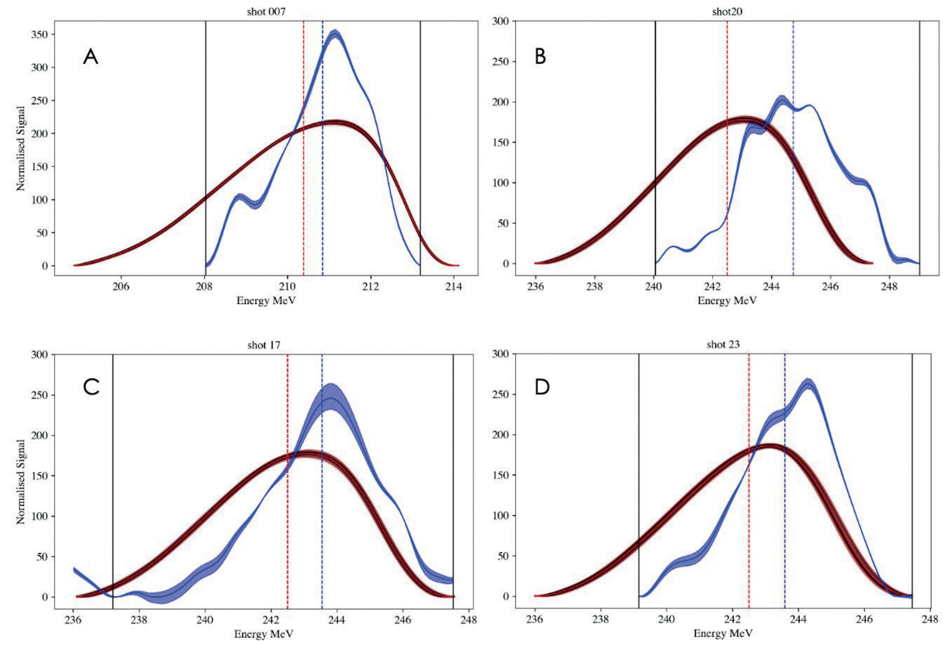

Figure 21. Energy profile of selected UNILAC ion pulses. The ions are Ca^{18+}. The mean pulse shape before laser drive is shown in red, and the modulated pulse in blue. Dotted vertical lines show the mean energy values. A: 4.383 MeV/u ions, ΔE = 0.5 MeV. B: 5.052 MeV/u ions, ΔE = 2.0 MeV. C: 5.052 MeV/u ions, ΔE = 1.0 MeV. D: 5.052 MeV/u ions, ΔE = 1.0 MeV.

In this experiment conducted at the Z6 target area, the PHELIX and nhelix lasers irradiated two opposing plastic targets with textured surfaces, such that the ablated plasma collided and mixed in the central region, creating a turbulent, magnetized plasma within about 15 ns of laser drive. Figure 20 shows an overview of the experimental setup. These targets were similar to those used in previous successful turbulent dynamo experiments [P. Tzeferacos (2018) Nature Commun. 9]. Collimated pulses of ions from the UNILAC (with period 9 ns) traverse the central region with the plasma. The change in the energy profile of the ion pulses can be observed via time of flight and is shown in Figure 21.

Analysis of the TOF data is encouraging. Ion pulses traversing the turbulent plasma within 1 period of its formation have a noticeable increase in their mean energy, up to 1%. Figure 21 shows a selection of such pulses. Electron density estimates extracted via a stopping power analysis, suggest that this cannot be a purely collisional effect. Charge state variation in the ions as they traverse the plasma can also affect the TOF signal, but the timescale of modulation in the TOF and the narrow energy bandwidth of the UNILAC suggest magnetic fields are responsible. Further spectrometry analysis and hydrodynamic simulation are ongoing and will better characterise the magnetic fields generated in this experiment.

Shaping of laser-driven carbon beams for future stopping power experiments at GSI/Z6

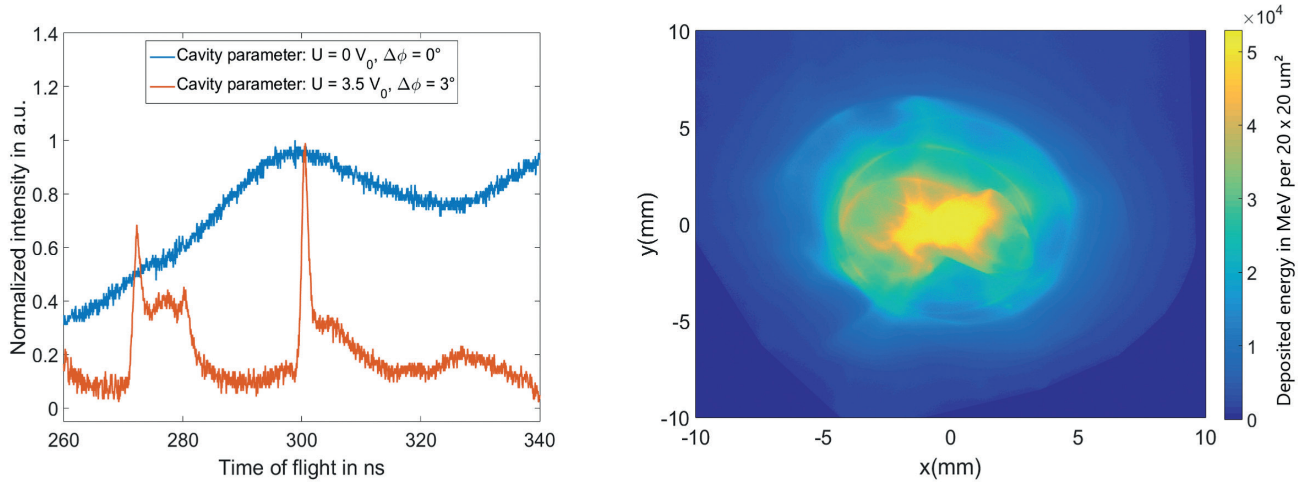

Figure 22. In the left picture the time of flight and the temporal profile of the transported carbon bunch at the end of the LIGHT beamline (3.25 m from its origin) is shown with a temporal compression by the rf cavity (red line) and without (blue line). The measurement was conducted with an ultra-fast diamond membrane detector (rise time: 40 ps), a fast photodiode (rise time < 1 ns) and an oscilloscope (bandwidth: 8 GHz). The right picture shows the deposited energy per area of the carbon bunch in an HD-V2 type RCF at the same position.

In an experimental campaign in January 2021, the Laser Ion Generation, Handling and Transport (LIGHT) collaboration was able to generate and shape carbon bunches that will be used in upcoming stopping power experiments for probing dense, highly-ionized matter. This was realised with the laser-driven ion beamline at the experimental area Z6 (LIGHT beamline), in which the PHELIX laser accelerates ions via the Target Normal Sheath Acceleration (TNSA). The spatial beam shaping (transport and focusing) of the carbon ions with the desired energy per mass of 0.6 MeV/u was realised with two pulsed high-field solenoid magnets. Since the transported ion bunch with charge state 4 had an energy spread of 1 MeV (FWHM), its pulse duration at the end of the beamline at the Z4 target chamber (3.25 m from its origin) was 50 ns (FWHM of the blue peak with a time of flight of 300 ns in the left picture of Figure 22). I. In order to reduce the energy spread of the bunch and especially its duration in the Z4 target chamber, the ions were also longitudinally shaped (temporal compressed) by a radiofrequency (rf) cavity. Thereby we were able to reduce the bunch duration to 1.23 ns (FWHM of the red peak with a time of flight of 300 ns in the left picture of Figure 22).

Typically, we collected 10^9 carbon ions per shot at the Z4 target chamber with a focal spot of 8.4 mm that contains 50% of the ions, of which 20 - 30 % can be temporally compressed. For stopping-power experiments, only a sub-aperture of this beam will probe a 0.5-mm-wide laser-generated plasma. Even in these conditions, the ion bunches available at the LIGHT beamline contain 10^2 to 10^3 more ions and are 5-10 times shorter than typical micro bunches of the UNILAC at Z6. Hence, the carbon bunches generated by the LIGHT beamline should improve signif-icantly the measuring uncertainties observed in our previous experiments [W. Cayzac (2017) Nat. Com. 8].

Currently, the nhelix laser at the experimental area Z6 undergoes a major upgrade. With the completion of this project, it will be possible to generate dense, highly ionized plasmas in the Z4 target chamber and thereby enable the conduction of the stopping-power experiments with the LIGHT beamline.

Acceleration of Electrons and Secondary Source Generation at PHELIX

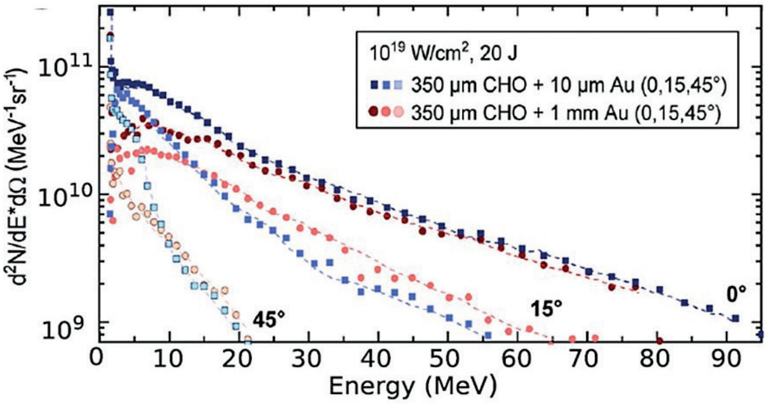

Figure 23. Electron spectra measured at 0°,15°, 45° to the laser axis in in-teraction of the PHELIX-pulse of 1019 W/cm2 intensity with CHO-foam stacked with a 10 µm Au foil (blue) and with a 1mm thick Au-converter (red). Figure taken from M. Guenther et al., Nat. Commun. 13 (2022).

In a three-week-long beam time, the plasma physics department in collaboration with JWGU Frankfurt con-tinued research on generation of Direct Laser Accelerated (DLA) [O. Rosmej (2020) Plasma Phys. Control. Fusion 62] beams of super-ponderomotive electrons with energies up to 100 MeV and 10 ns of nC charge, and their ap-plications for interdisciplinary FAIR-relevant research.

High-current well-directed beams of DLA electrons were produced during the interaction of relativistic laser pulses with pre-ionized foam of near-critical electron density. Figure 23 shows spectra of DLA electrons measured by means of 0.99 T magnetic spectrometers placed at 0°, 15° and 45° in relation to the laser axis. The highest electron energy of up to 100 MeV and the effective temperature of 14 MeV were measured along the laser propagation direction.

Three-dimensional particle-in-cell simulations provided a good agreement with the measured electron energy distribution and were used to study synchrotron radiation from the DLA-accelerated electrons [4]. The resulting x-ray spectrum with a critical energy of 5 keV reveals an ultrahigh photon number of 7×10^{11} in the 1–30 keV photon energy range for 20 J of the focused laser energy [5], what is comparable with photon number predicted for 1 kJ PETAL.

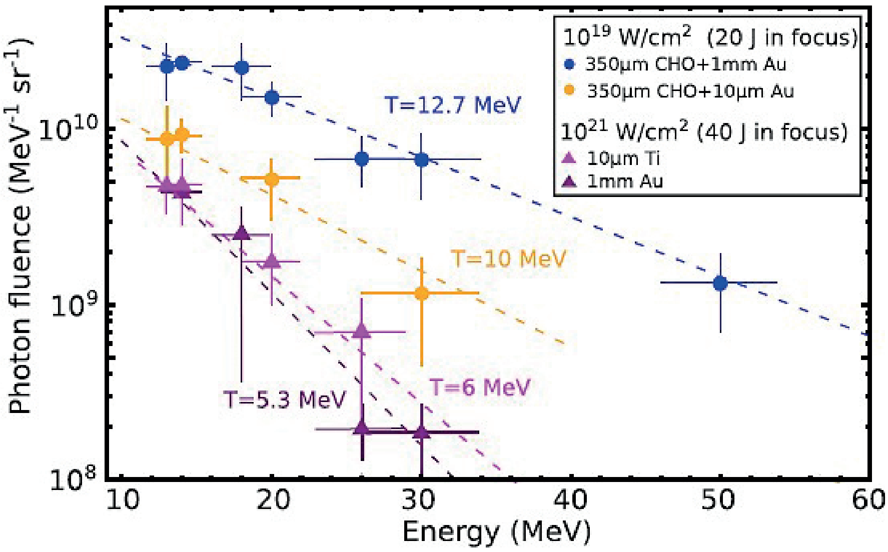

Figure 24. Bremsstrahlung spectra generated by DLA-electrons propagating in high Z foils: blue and yellow dots are data obtained at 10^{19} W/cm2 laser intensity in shots onto foams stacked with 1 mm Au and 1 mm Au-foil correspondently; magenta and purple triangles are data obtained in shots at 10^{21} W/cm2 laser intensity directly on foils. The error bars represent the accuracy of reaction yield and the width of nuclear resonance used for spectral reconstruction. Dashed lines are exponential fits of the experimental data. Figure taken from M. Guenther et al., Nat. Commun. 13 (2022).

Using low-density foams irradiated with PHELIX-pulse of relativistic intensity, we demonstrated, for the first time, an application of DLA electrons for production of MeV bremsstrahlung radiation with record-breaking conversion efficiency achieved at moderate relativistic laser intensity [M. Guenther (2022) Nat. Commun. 13]. Figure 24 shows the spectral intensity of the source in the range of 10-50 MeV measured using photo-disintegration reactions method in the case of foam stacked with 1-mm-thick Au-plate (blue) and thin Au-foil (yellow). In the first case, the photon emission reached 10^{12} ph/sr for photons with an energy above 10 MeV, which corresponds to a conversion efficiency of 1.4 %. The photon energy distribution was approximated by exponential functions with effective temperatures of 12.7 MeV and 10 MeV respectively, which are twice higher than in direct shots onto foils at about 10^{21} W/cm^2 laser intensity (see Figure 24 magenta and purple triangles). In addition, we report a record neutron flux of $(1.4 \pm 0.2) \times 10^{10}$ per shot measured in gamma-driven nuclear reactions. Such beams of MeV particles and radiation are excellent tools, which can be used for research in plasma physics, nuclear astrophysics, materials research, radio oncology, or biophysics.

Outlook for 2022

GSI plans a new run with the accelerator during the first semester of 2022, where plasma physics will employ protons for PRIOR-II and heavy ions like uranium and lead for the HIHEX setup at the HHT experimental area.

To provide backlighter capabilities at FAIR for day-1 experiments in 2025, the construction of the FLAX laser will start after many years of R&D. Other projects like the upgrade of the nhelix laser at Z6 will continue and should be completed in 2022.

Selected publications of 2021

- [1] Tahir, N. A. ; Shutov, A. ; Neumayer, P. ; et al.: Production of warm dense water in the laboratory using intense ion beams at FAIR: Application to planetary physics. Physics of plasmas 28(3), 032712 (2021), DOI:10.1063/5.0037943
- [2] Ohland, J. B. ; Zobus, Y. ; Eisenbarth, U. ; et al.: Alignment procedure for off-axis-parabolic telescopes in the context of high-intensity laser beam transport. Optics express 29(21), 34378 (2021), DOI:10.1364/OE.439658
- [3] Hornung, J. ; Zobus, Y. ; Roeder, S. ; et al.: Time-resolved study of holeboring in realistic experimental conditions. Nature Communications 12(1), 6999 (2021), DOI:10.1038/s41467-021-27363-9
- [4] Shen, X. F. ; Pukhov, A. ; Günther, M. ; et al.:Bright betatron x-rays generation from picosecond laser interactions with long-scale near critical density plasmas. Applied physics letters 118(13), 134102 (2021), DOI:10.1063/5.0042997
- [5] Rosmej, O. ; Shen, X. F. ; Pukhov, A. ; et al.: Bright betatron radiation from direct-laser-accelerated electrons at moderate relativistic laser intensity. Matter and radiation at extremes 6(4), 048401 (2021), DOI:10.1063/5.0042315

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 over 90 members with background in physics, biology, chemistry, and engineering.

International Biophysics Collaboration at FAIR

The Biophysics Department is part of the APPA pillar at FAIR. The International Biophysics Collaboration (IBC) is a large network of accelerator facilities in operation or under construction with scientific programs in biomedical applications. In 2021, despite the COVID-19 restrictions, IBC implemented 19 experiments selected by the BIO-PAC in June 2020 in the framework of FAIR Phase-0. Moreover, IBC implemented 6 experiments selected by ESA within the AO-IBER-19 proposal and 3 that had been selected in the AO-IBER-17 but could not be completed in 2020 due to the travel limitations imposed by the coronavirus pandemics. More than 50% of these experiments were performed by IBC groups external to the GSI Biophysics Department

Awards

Several members of the Biophysics Department received awards in 2021. Particularly relevant are the Giersch Award for outstanding doctoral thesis to Dr. Tabea Pfuhl, the 23. Christoph Schmelzer Award to Dr. Felix Horst and two new professors at the TU Darmstadt: Dr. Christian Graeff is now professor (W2) at the Department of Electrical Engineering and Information (ETIT), while Dr. Burkhard Jakob has been nominated Honorary Professor at the Department of Biology.

Highlights in 2020

This year was exceptionally productive for the Biophysics Department, with 51 peer-reviewed papers in the GSI repository [1,2]. A few highlights are provided here:

FLASH

Ultra-high-dose rate radiotherapy (FLASH) is the new frontier of cancer therapy. A few years ago, in fact, a French-Swiss collaboration has shown that exposure of animals to very high intensities (>40 Gy/s) strongly reduces normal tissue toxicity whilst maintaining tumour control. These high intensity cannot be achieved with X-rays, but have been measured with electrons (from linacs) and protons (accelerated in cyclotrons). Using the HIT synchrotron in Heidelberg, we have now published the first results of FLASH with ^{12}C-ions [3]. Moreover, in the frame of FAIR Phase-0 we have now used the SIS18 synchrotron at GSI in FLASH regime (NN). While at HIT we reached 50 Gy/s in a 10x10 mm^2 spot with 5×10^8 C-ions per spill, at GSI we could reach 5×109 C-ions per spill, and therefore 100 Gy/s in a 20x20 mm^2, which allows animal experiment [4].

BARB

The ERC Advanced Grant “Biomedical Application of Radioactive ion Beams” (BARB) performed the first physics experiments in 2021 both at the fragment separator (FRS) and in Cave M [5. BARB is an inter-pillar FAIR experiment, a strong collaboration between APPA (Biophysics Department) and NuSTAR (FRS). The beamline connecting FRS to cave M was commissioned for the first time, allowing the first tests of the γ-PET detector prototype developed at the Ludwig-Maximilian-Universität in Munich (Figure 26). First images of the β^+-emitting isotopes ^{10}C, ^{11}C, ^{14}O and ^{15}O were also collected at the FRS using the PET of the University Medical Central Groningen. Careful measurements of the fragmentation cross-sections of these radioactive isotopes were also completed at FRS.

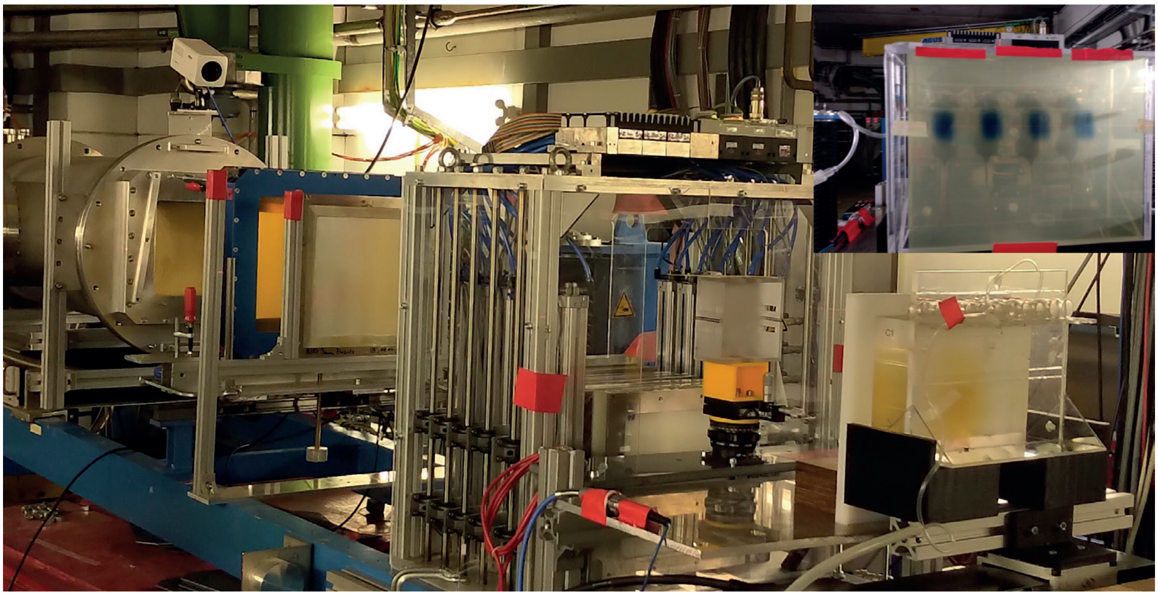

Figure 25. Experimental setup in Cave A for FLASH radiotherapy tests with heavy ions. The intensity monitor is a He-filled parallel-plate ionization chamber and the dose is measured with a pin-point chamber in a polyethylene block. The inset on top-right corner shows a GAFchromic image of the dose delivered by ^{12}C-ions in the thorax of the mice in FLASH conditions. Photo by Dr. Uli Weber, reproduced under CC-BY 3.0 license.

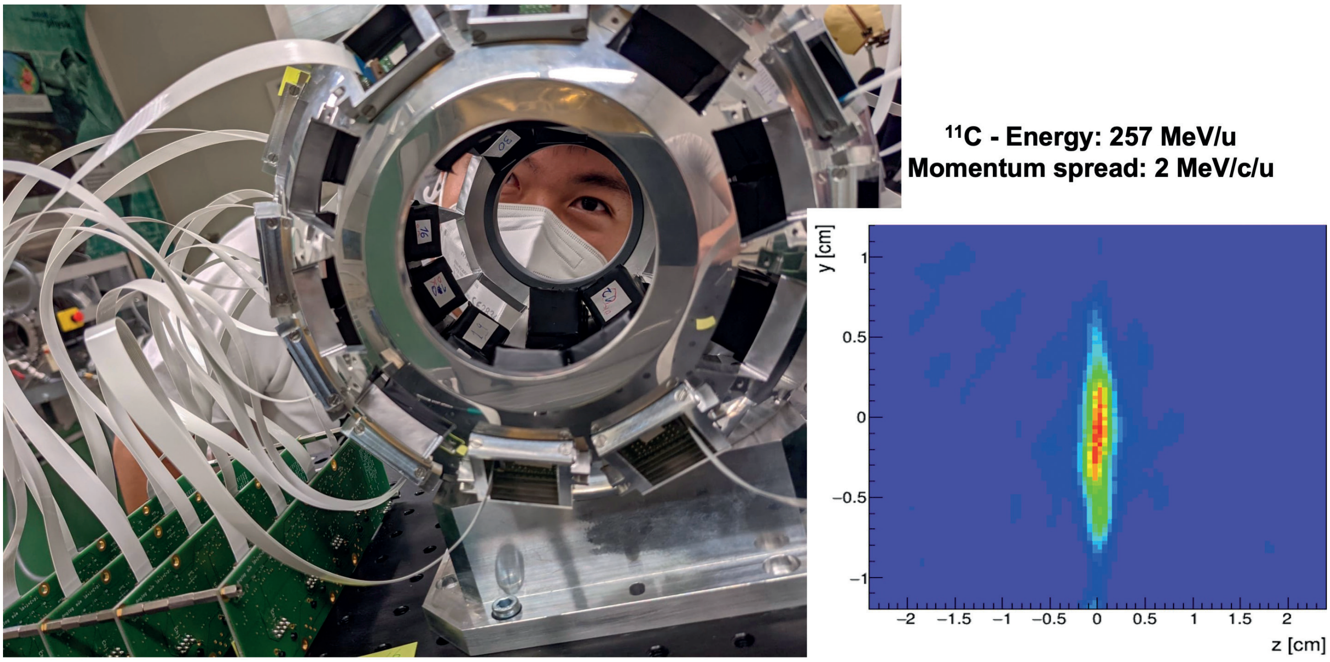

Figure 26. Image of the y-PET detector installed in Cave M to visualize radioactive beams. A PET image of the ^{11}C beam is shown in the right panel. Image by Dr. Daria Boscolo, reproduced under CC-BY 3.0 license.

Cancer vaccines and heavy ion therapy

We are all very familiar with the mRNA technology that led in 2020 to the very fast development of an effective vaccine against SARS-CoV-2. BioNTech and its research non-profit sister company TRON in Mainz played a major role in developing and producing these vaccines. Interestingly, mRNA vaccines in Mainz were originally developed against cancer, because specific cancer mutations can be detected and use to target metastatic tumors. We have now performed the first experiment with TRON about the combination of mRNA cancer vaccine and carbon ion irradiation in a colon carcinoma murine model. As shown in Figure 27, the combination of neoantigen-encoding (neoAg) RNA lipoplex (RNA-LPX) and heavy ions controls the tumor much better than radiation or vaccine alone.

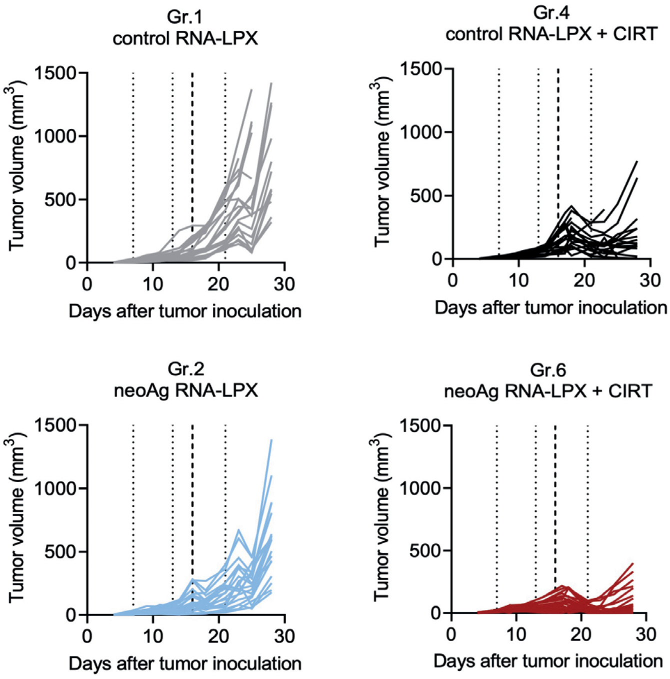

Figure 27. Colon carcinoma tumor growth after treatment with sham LPX (group 1); neoAg RNA-LPX vaccine (group 2); carbon ion radiotherapy (CIRT) alone (group 4); or a combination of vaccine plus CIRT (group 6). Each line represents a different mouse. The curves shows that the combined treatment achieves the best tumor control. Image by TRON, reproduced under CC-BY 3.0 license.

Outlook for 2021

Beamtime in Spring-Summer 2021 will be mostly dedicated to repeat experiments in 2020. New exciting idea will be proposed in the Bio-PAC in September 2022 and in the new AO-IBER-22 sponsored by ESA. The Department will also add a new group, space radiation biology, whose group leader is under recruitment. The new group will lead the IBER project and will exploit the new laboratory infrastructure under construction in the Annex building. There will be also a strong investment in AI-based systems in heavy ion treatment planning, a topic which is rapidly growing and where the Department's expertise in medical physics software can largely contribute. Finally, we will make the first test of the galactic cosmic ray simulator, sponsored by ESA, that will set GSI as the only EU facility able to simulate deep space radiation field on Earth.

Selected publications of 2021

- [1] Durante, M. ; Debus, J. ; Loeffler, J. S..: Physics and biomedical challenges of cancer therapy with accelerated heavy ions. Nature reviews physics 3(12), 777 - 790 (2021) [10.1038/s42254-021-00368-5]
- [2] Durante, M.: Failla Memorial Lecture: The Many Facets of Heavy-Ion ScienceRadiation research 195(5), 403-411 (2021) [10.1667/RADE-21-00029.1]
- [3] Tinganelli, W. ; Sokol, O. ; Quartieri, M. ; et al.: Ultra-High Dose Rate (FLASH) Carbon Ion Irradiation: Dosimetry and First Cell Experiments. International journal of radiation oncology, biology, physics 112(4), 1012 - 1022 (2022), DOI:10.1016/j.ijrobp.2021.11.020
- [4] Weber, U. ; Scifoni, E. ; Durante, M.: FLASH radiotherapy with carbon ion beams. Medical physics 49(3), 1974 - 1992 (2022), DOI:10.1002/mp.15135
- [5] Boscolo, D. ; Kostyleva, D. ; Safari, M. J. ; et al.: Radioactive Beams for Image-Guided Particle Therapy: The BARB Experiment at GSI. Frontiers in oncology 11, 737050 (2021) [10.3389/fonc.2021.737050]

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

Coordination: Prof. Dr. Joachim Stroth (JWGU Frankfurt & GSI)
Authors: Tetyana Galatyuk, Joachim Stroth

Despite difficult working conditions all departments managed to pass many milestones, reviews in all the subprojects and to achieve impactful physics results. This demonstrates the strength and capabilities of HADES, CBM and ALICE departments. The FAIR civil construction is progressing and the roof of the SIS100 experimental hall, the home of CBM and HADES, has already been poured. This is very reassuring and motivating. CBM, being the first customer of SIS100 beams, pursues with high priority the completion of the FAIR Day-1 experimental setup to be ready by end of 2025. The construction of CBM detectors and the related infrastructure (front-end electronics, LV, HV, cooling and gas system) is ongoing and/or being prepared. Following the FAIR Site & Buildings plans, the installation of first CBM experiment infrastructure could start in the second half of 2022. Work on the dipole foundation and upstream platform design has progressed substantially. After successful completion of the research and development in 2021, series production of the detector components is planned from 2022 on. In order to make use of first modules of CBM detector systems which became available, CBM is successfully pursuing several FAIR Phase-0 activities. The CBM department, together with the GSI Detector Laboratory, is responsible for the fabrication and assembly of the Silicon Tracking System (STS). The expertise of the groups in instrumentation and analysis is also the reason for a strong cooperation with the Baryonic Matter at Nuclotron (BM@N) experiment, which is pursuing fixed-target experiments at the JINR's Nuclotron. The BM@N-STS technology is adopted from the STS of the CBM experiment. Financial support for this activity comes through the EU project CREMLINplus and the Russian-German Roadmap agreement. An important element of the timely realization of CBM is the ongoing commissioning of the trigger-less data acquisition and online event reconstruction. The mCBM setup has been specifically installed at GSI to commission and optimize the complex interplay of the different detector systems with the triggerless, free-streaming data acquisition and the fast online event reconstruction and selection.

In 2021, the ALICE department at GSI carried major responsibilities regarding the upgrade of the Time Projection Chamber (TPC), which is the heart of the ALICE tracking and particle-identification system. Scientists of the ALICE department have been involved in the operation, calibration and maintenance of the new detector system. In Run3 the LHC will provide Pb-Pb collisions at a rate of 50 kHz, which required a replacement of the TPC readout chambers with GEM-based detectors and the development of a new Online-Offline computing framework. In both projects the ALICE department at GSI, together with the Scientific Computing Department and the Detector Laboratory played a key role. The commissioning of the upgraded systems culminated in one week of operation with LHC "pilot beams" in December 2021. The new readout system was put into operation and it was found that the TPC met all specifications. A large fraction of the activity in 2021 was dedicated to a timely completion of the HADES detector upgrade. To enhance the physics performance for investigation of exclusive decay channels in pp reactions, HADES decided to instrument the very forward solid angle with tracking and time-of-flight detectors. In a joint effort of PANDA and HADES the instrumentation of the forward hemisphere of the HADES spectrometer was completed. Furthermore, the fifth sector of the electromagnetic calorimeter has been installed and equipped with the dedicated readout electronics, newly developed sensors based on Low Gain Avalanche Detector technology were employed as in-beam detectors, the upgrade of the data acquisition system to deal with event rate of up to 50 kHz for low multiplicity has been completed. Full detector and data acquisition system were successfully tested during the commissioning run in February 2021.

Substantial progress in the data analysis activities has been also made. The analysis of 15 billion Ag+Ag events at 1.23A GeV and 1.58A GeV collected by HADES progressed substantially and results for publications have been produced for the dielectron continuum, weak decays, Λ-hyperon production, azimuthal anisotropy and global polarization, as well as meson production. The ALICE group played a key role in analyses related to heavy-flavor particle and light (anti) nuclei production in pp and Pb-Pb collisions at top LHC energies. Important publications have come out as addressed in the sections below.

3.1 ALICE at GSI

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

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

The ALICE department at GSI has been playing a leading role since many years in most relevant aspects of the ALICE Collaboration. Major responsibilities regarding the operation, calibration, maintenance, and upgrade of the Time Projection Chamber (TPC), which is the heart of the ALICE tracking and particle-identification system, rest with the members of the ALICE group and the GSI Detector Laboratory. The ALICE group, in a joint effort with the Scientific Computing Department, played a key role in the development and integration of the new online computing system, designed to address the major challenge of sampling the full 50 kHz Pb-Pb interaction rate, improving the previous limitations by a factor of about 100. 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.

Highlights in 2021

Physics results from Run2 data analysis

Among the most relevant highlights of this year, in which the GSI-ALICE group played a major role, there are measurements related to heavy-flavor particles and to light (anti)nuclei.

The measurement of heavy-flavor hadron production in hadronic collisions provides crucial information on perturbative and non-perturbative aspects of the dynamics of charm quark production and hadronisation. The measurement of a comprehensive set of charmed hadrons enabled the determination of the total charm quark production cross section with unprecedented accuracy, as well as of the charm ‘fragmentation fractions’, that are the probabilities of the various charm hadron species to be formed (shown in the left panel of NN). It is often assumed that the fragmentation of charm quarks to charmed hadrons is universal among collision systems. ALICE reports that this is not the case: the observed charmed hadron distribution in proton-proton collisions is very different from previous measurements at electron-positron and electron-proton colliders. The ALICE measurements have stimulated an intense theoretical activity for their interpretation, mainly in terms of hadron formation mechanisms that take into account the surrounding environment of strongly-interacting particles [1, 2].

The ALICE experiment is making strides towards understanding how charm and beauty quarks might thermalize within cooling droplets of quark–gluon plasma at the LHC, shedding light on the extreme conditions of the early universe. Among the most striking features of the QGP formed at the LHC is the development of “collective” phenomena, as spatial anisotropies are transformed by pressure gradients into momentum anisotropies. Heavy quarks are therefore powerful probes of properties of the QGP. As they traverse the medium, they interact with its constituents, gaining or losing energy depending on their momenta. The ALICE Collaboration has measured the elliptic flow coefficients (ν_2) of hadrons with open and hidden charm and beauty. The GSI-ALICE group contributes strongly to measurements of the elliptic flow of electrons from beauty-hadron decays in Pb–Pb collisions. Open beauty hadrons, whose mass is dominated by the b quark, are also seen to flow, and in the low-pT region an apparent mass hierarchy is seen: the lighter the particle, the larger the elliptic flow, as expected in a hydrodynamical description of QGP evolution (see the right panel of Figure 28). Theoretical descriptions of elliptic flow are also making progress. Models of heavy-flavor flow need to include a realistic hydrodynamic expansion of the QGP, the interaction of the heavy quarks with the medium via collisional and radiative processes, and the hadronization of heavy quarks via both fragmentation and coalescence [3].

 DOI:10.15120/GSI-2022-00454

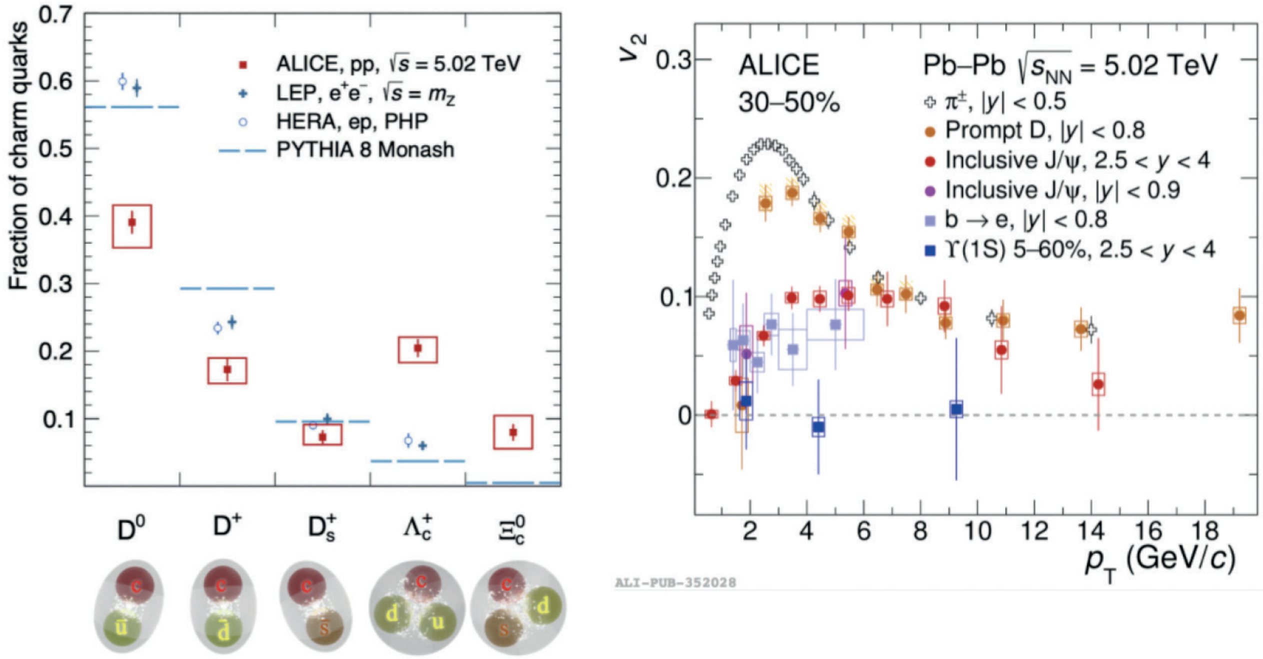

Figure 28. (Left panel) Charm quark fragmentation fractions into the most abundant charmed hadron species in pp collisions at √s = 5.02 TeV. (Right panel) ALICE measurements of differential elliptic flow coefficients for charged pions, D mesons, J/ψ mesons, electrons from beauty-hadron decays and Γ(1S) mesons in semi-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

Among other particles, a large number of light nuclei such as the deuteron, triton, ^{3}He, ^{4}He, and their corresponding antinuclei are produced and can be measured with very good precision by the ALICE experiment thanks to its excellent tracking and particle-identification capabilities via specific energy loss and time-of-flight measurements. Elucidating their production mechanisms is not only relevant related to the fundamental understanding of the strong interaction and the process of hadronization, but these studies are also of prime importance for space-born cosmic-ray measurements that intend to shed light on the nature of the mysterious dark component that is supposed to account for for a large fraction of matter in our universe. The ratios between the p_T-integrated yields of nuclei and protons as a function of multiplicity have been recently analysed [4]. Figure 29 shows the measurement for different collision systems and energies for deuterons (d/p) and helium (^{3}He/p) in the left and right panels, respectively. For both d/p and ^{3}He/p: the ratio increases as a function of multiplicity and eventually saturates at high multiplicities. This trend can be interpreted as a consequence of the interplay between the evolution of the yields and of the system size with multiplicity. The measurements are compared with the prediction of the Canonical Statistical Model and the coalescence model. The comparison highlights that the coalescence mechanism might play an important role in the formation of light (anti)nuclei.

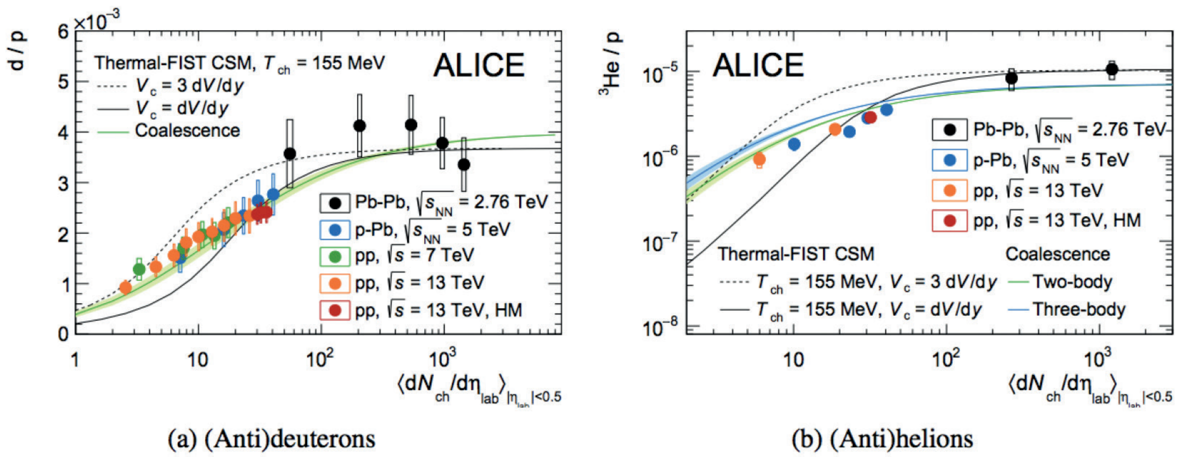

Figure 29. Ratio between the yields of nuclei and protons as a function of multiplicity for (anti)deuteron (a) and (anti)helium (b).

Commissioning of the upgraded Time Projection Chamber and other preparations for run3

The ALICE group at GSI has a central role in the commissioning of the upgraded TPC, and in the realization of the new Online-Offline facility and software framework (the O2 project). The ALICE TPC has undergone an upgrade in the recent few years. This upgrade involved the exchange of its readout chambers (of which a large part had been assembled at GSI in the previous years) and electronics, in order to cope with the requirements defined by the task to read out all collisions at an interaction rate of 50 kHz. After successful execution of the upgrade in a clean room at the surface of the ALICE experimental site, the TPC was lowered back into the ALICE cavern and brought close to its final position inside the ALICE magnet in the second half of 2020. At the end of 2020 the connection of the TPC to the final services (low voltage for the electronics, high voltage for the drift field cage and for the new GEM-based readout chambers, water for cooling, gas pipes, and fiber patch cords for the readout and control of the on-detector readout electronics) could start. This activity spanned well into the year 2021 and was significantly impacted by the COVID-19 pandemic, as travelling of the needed manpower could not take place due to severe travel restrictions during that period. The difficulties could be mitigated by relying on the GSI staff that was permanently stationed at CERN during that period, and by involving other manpower locally available, which had to be trained and supervised appropriately by the local experts.

The remainder of the year was used for the commissioning of the detector and the O2 facility. This included the verification of the state and functionality of the 72 low voltage channels, the 1152 high voltage channels, the 3276 front-end cards including their optical control links, the 6552 optical readout links, and the other services. In particular, the verification of the leak tightness of the 60 cooling loops required a lot of time and quite some manpower. The last leak was identified and fixed only in January 2022. Moreover, the verification of the proper gas mixture inside the TPC active volume requires several measurements and cross checks using e.g. data taken with the TPC laser system. The laser system itself also needed to be re-installed in the ALICE experimental cavern, and alignment with respect to the detector. Several campaigns aimed at the collection of different calibration data have already been executed.

One issue that required deep investigation and the development of mitigation strategies concerned fatal communication issues (loss of communication) that appeared, with time, on a considerable fraction (up to 1%) of the 3276 front-end cards. The issue could be traced to the optical transceivers installed on each front-end card. The Versatile Transceiver (VTRx) is a component developed at CERN as part of a radiation hard readout and control link. The VTRx was produced in large quantity (18000 pieces) and is used on the ALICE TPC front-end card, but also on other readout cards employed in ALICE as well as in other experiments both at CERN and elsewhere (e.g. in CBM at FAIR). In fact, other groups had noticed similar communication losses starting in 2018 (CMS HCAL) and later (ALICE inner tracking system). It took a while to understand the severity and cause of the issue. It was found that a link loss is usually preceded by a slow downward drift of the received signal strength indicator (RSSI) that is measured on the receiver (down) path on the VTRx component. In fact, up to half of the 3276 VTRx installed on the TPC showed drifting (unstable) RSSI currents. So a massive communication failure seemed a likely scenario for the future.

After a thorough investigation involving different groups including the one responsible for the development of the VTRx, the issue could be traced to outgassing from not properly cured glue used in the assembly of the devices. The outgassing starts once the component heats up during operation. Condensation on the tip of the plugged fiber then obstructs the light path, leading to the described observations. The proposed mitigation strategy includes the extraction of all VTRx from the affected detectors, and post-curing of the glue by baking the components in an oven for 500 hours at 85 ^{o}C. This approach was tested and confirmed to work. It would, however, in the case of the TPC, have introduced a considerable delay of many months, due to the difficulty to extract and re-install the large number of components on the TPC. Instead, an alternative approach was followed where the VTRx components were added to the active cooling infrastructure for each front-end card by the addition of a small cooling fin, made of copper, that serves as a heat bridge from the warm VTRx to the water cooled envelope surrounding each front-end card. The reduction of the operational temperature of the VTRx removes the outgassing and thus the communication issues. The cooling fins were installed on the 3276 front-end cards in the summer of 2021 during a dedicated campaign over the course of three weeks. The activity was planned and led by GSI, and involved manpower from GSI. It did not lead to any delay in the commissioning of the ALICE experiment.

Furthermore, the commissioning of the upgraded ALICE experiment took place, which culminated in one week with “pilot beams”, which included proton-proton collisions at 900 GeV provided by the CERN Large Hadron Collider LHC. The final readout scheme with a first data reduction step from 3.5 TBytes/s down by a factor of more than five and a second reduction step by employing online tracking in the new Online-Offline facility on Graphical Processing Units (GPU) could be exercised. The TPC performed according to specifications. Figure 30 shows an event display (left panel) and the online performance of the TPC in terms of particle identification (right panel). Among other tasks, experts from GSI serve as on-calls during the commissioning of the experiment.

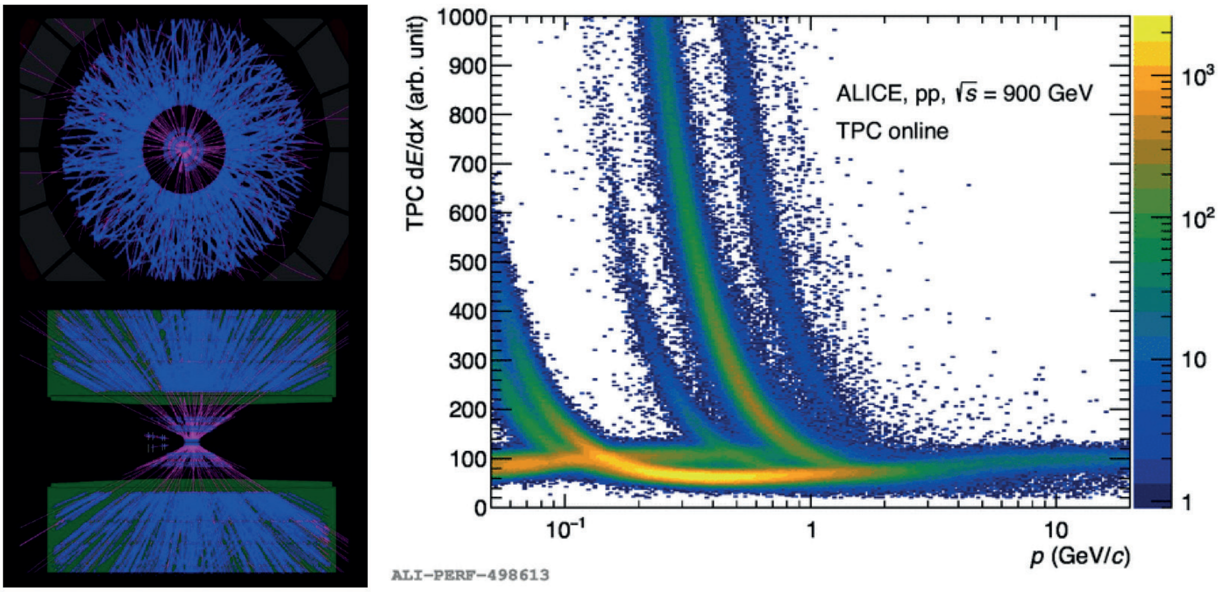

Figure 30. (Left panel) Event display showing data from the pilot run in October 2021. (Right panel) Energy loss of charged particles (dE/dx) as a function of momentum p measured with the TPC. Online plot from Quality Control during pilot run.

Selected publications of 2021

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- [2] Acharya, S. ; Adamova, D. ; Adler, A. ; et al.: Measurement of the Cross Sections of Ξ^0_c and Ξ^+_c Baryons and of the Branching-Fraction Ratio BR(Ξ^0_c->$\Xi^-e^+\nu_e$)/BR(Ξ^0_c->$\Xi^-\pi^+$) in pp collisions at 13 TeV. Physical review letters 127(27), 272001 (2021), DOI:10.1103/PhysRevLett.127.272001
- [3] Acharya, S. ; Adamova, D. ; Adler, A. ; et al.: Elliptic Flow of Electrons from Beauty-Hadron Decays in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Physical review letters 126(16), 162001 (2021), DOI:10.1103/PhysRevLett.126.162001
- [4] Acharya, S. ; Adamova, D. ; Adler, A. ; et al.: Production of light (anti)nuclei in pp collisions at √s = 13 TeV. Journal of high energy physics 01(1), 106 (2022), DOI:10.1007/JHEP01(2022)106

3.2 CBM at FAIR

Head: Prof. Hans Rudolf Schmidt (Univ.Tübingen & GSI)
Authors: Alberica Toia, Maksym Teklishyn, Johann Heuser, Hans Rudolf Schmidt

Highlights in 2021

The STS detector of the CBM experiment

Figure 31. Module assembly section in the clean room of the GSI Detector Laboratory.

The commissioning of the CBM experiment and the first operation with SIS100 beam is planned for 2025/26. After successful completion of the research and development in 2021, series production of the detector components is planned from 2022 on. The CBM department, together with the GSI detector laboratory, is responsible for the fabrication and assembly of the Silicon Tracking System (STS). The envisioned high-rate operation of the STS requires complex cooling of the front-end electronics at near cryogenic temperatures, resulting in ambient temperatures for the sensors of about -10 °C. To ensure operation with a very low failure rate, careful tests must be set up at all stages of series production - modules, ladders, C-frames, units. It must be guaranteed that the fragile objects survive unavoidable high temperate gradients. In 2021 we have begun to design and build the corresponding setups for these series production tests. In addition, the performance of the detector system as such is being scrutinized in a test experiment: mCBM. It includes a mSTS, which consist of two small versions of the STS tracking layers. A corresponding suite of tests during assembly as well performance results from mSTS are detailed further below.

Testing setups for STS modules and ladders

The STS detector of the CBM experiment features a high degree of the integration of its components. To ensure reliable performance and stable operation of the assembled detector, an extensive set of test procedures is required. Each component of the setup starting from the individual ASICs of the STS front-end electronics and ending with the equipped tracker units will undergo functionality tests of various degrees of sophistication. These tests will be performed in parallel with the system integration and will require dedicated test setups.

The first procedure to be performed with the newly assembled module is its extensive functionality check at room temperature, starting from the electrical characteristics of the sensor and continuing with the ADC calibration

 DOI:10.15120/GSI-2022-00454

procedure. It requires a module test stand in a light-tight enclosure which also protects its interior from external electromagnetic fields. This system (see Figure 32, left) is being implemented in the STS integration area at the GSI Detector Laboratory and will be further multiplied for the other production centers. The next iteration of the module testing hardware will feature a self-containing module carrier frame with mechanical support of the fragile parts of the detector and embedded interfaces to access power and data links (see Figure 32, right).

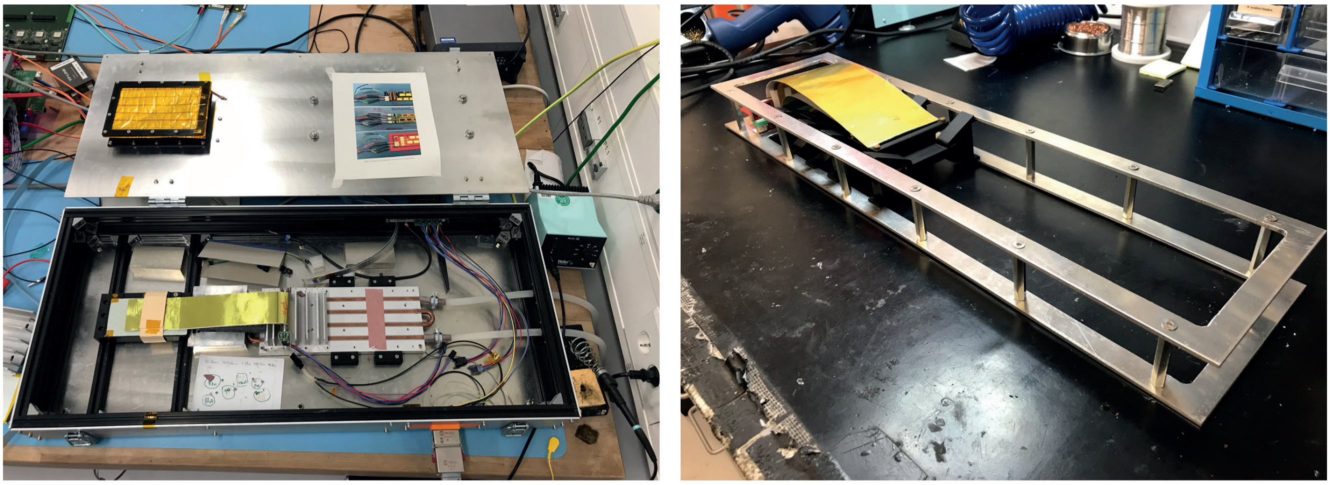

Figure 32. Module test stand (left) and module carrier frame (right).

The module test stand is operated at room temperature with water cooling for the read-out electronics, which is provided by a stand-alone chiller next to the setup. The stand-alone GBTxEMU is used in the DAQ chain for module read-out. Typically, one would expect about one day to be spent for the characterization of one module with the given setup.

The next step for the evaluation of the module performance will be a “burn-in” procedure dedicated to testing of the thermal interfaces of the system. The setup consists of a climatic chamber with a mainframe suited to host up to 5 detector modules of various dimensions. In addition, the read-out electronics of the modules will be cooled by a Julabo chiller with NOVEC cooling liquid (see Figure 33, left). Both the climatic chamber and the chiller are capable to yield temperatures as low as -40 °C providing ample cooling power for conditions as required during module operation in CBM. Outside of the chamber there will be a sufficient number of read-out electronics boards to have permanent access to the data from modules being tested. The current approach involves a stand-alone DAQ chain in a similar manner as for the module test box.

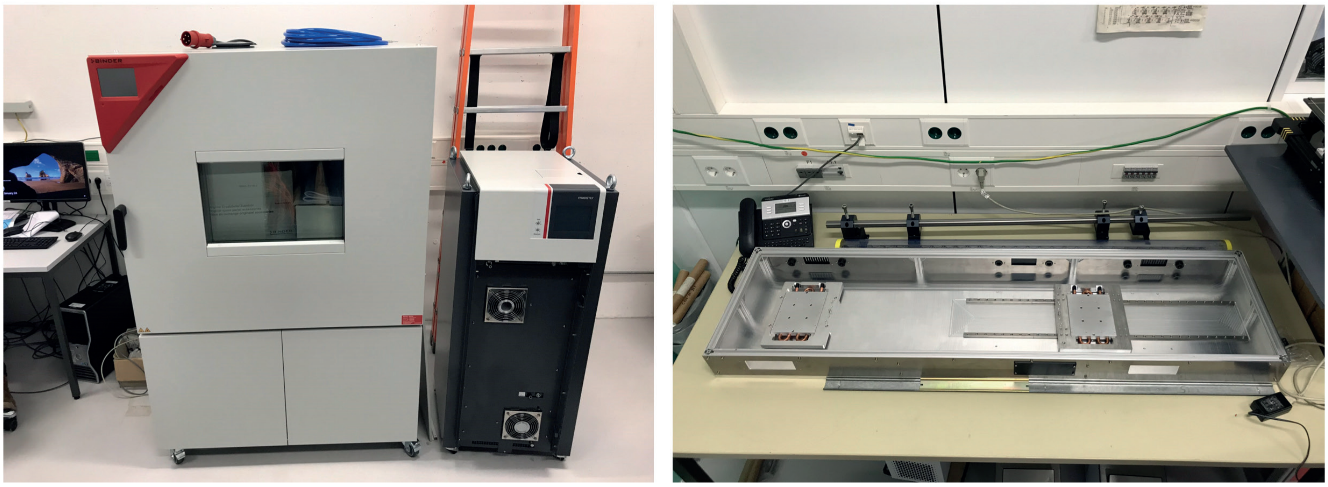

Figure 33. Climatic chamber and Julabo chiller for the module “burn-in” setup (left). STS ladder test box (right).

The “burn-in” procedure for the detector modules will involve repeated temperature cycling from room temperature down to - 40 °C for the readout electronics and –10°C for the ambient temperature inside the climatic chamber. The cycle will be repeated 10 times to check the modules’ performance under thermal stress. The total duration of the procedure for a set of 5 modules is estimated as 1-3 days depending on the type of test performed. Ideally, each of the module production centers should have this kind of setup.

The modules that successfully passed burn-in cycling process will be delivered to the clean room of the GSI Detector Laboratory to be assembled on the detector ladder. After the assembly, the ladder will undergo a series of basic functionality tests to verify the integrity of its components. These tests will be conducted in the ladder test setup at GSI (see Figure 33, right). The ladder placed inside of an aluminum light-tight box will be checked for the sensors' high-voltage standing and basic communication. Two stand-alone chillers will provide water cooling necessary for the operation of the read-out electronics of up to 10 modules on a single ladder. The typical duration of such tests is expected to be within few hours. This setup is only foreseen in the GSI STS laboratory.

In addition to the test setups described above there will be others dedicated to the tests of the elements of the read-out chain, the power electronics, and also larger integrated structures: detector units equipped with multiple ladders as well as the fully assembled STS detector.

mSTS performance results

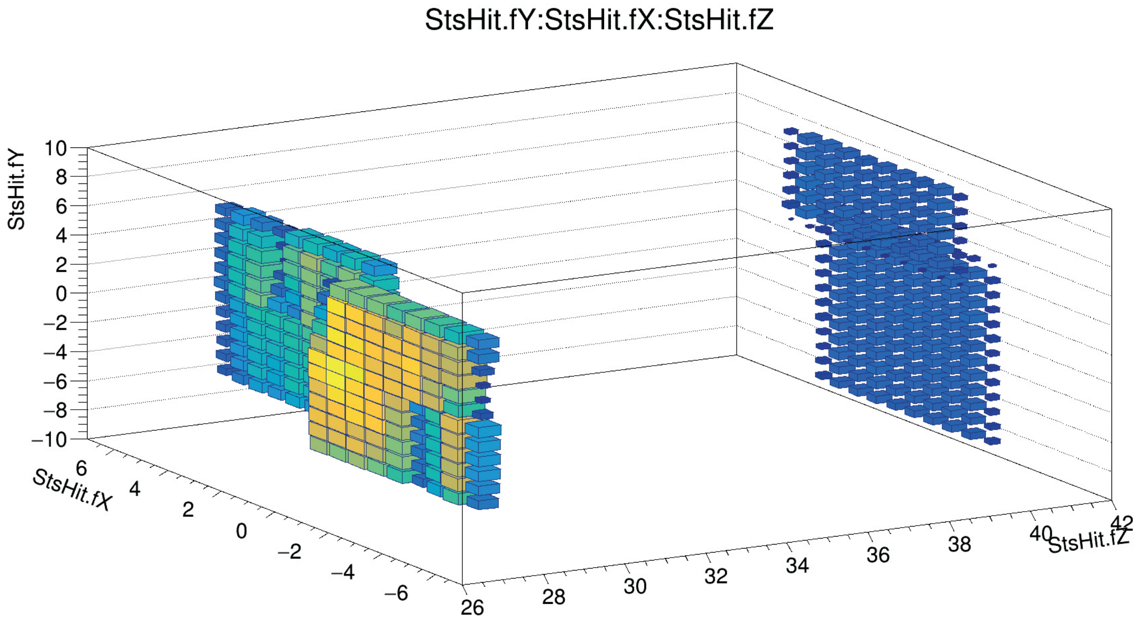

Figure 34. Space distribution of reconstructed mSTS hits in the two tracking stations.

In the mCBM 2021 beam campaign at SIS18 (GSI) O+Ni collisions at 2 AGeV were measured with a beam intensity of up to 10^{10} ions per spill, and approximately 500 kHz interaction rate. The mini-STS (mSTS) demonstrator ´consisted of two tracking stations covering a total area of 12 × 12 cm^2 and 18 × 18 cm^2 respectively They were arranged in 4 units with a total of 11 modules: their double-sided double-metal silicon microstrip sensor was covering a surface of 62 x 124 mm2 for two modules, and 62 x 62 mm^2 for 9 of them. For their read-out they were equipped with two Front-End Boards (FEBs) each comprising 8 SMX (STS/MUCH-XYTER) ASICs, plus two service FEBs for pulser signal injection, 5 common read-out boards (CROB) for data aggregation, and 5 power boards (POB) providing low voltage for FEBs and ROBs.

Prior to installation in the mCBM cave an energy calibration has been performed to adjust the dynamic range of the front-end ASICs' ADC using a calibrated internal pulse generator and dedicated counters in the chip in order to record S-curves. The estimated baseline noise level corresponds to an equivalent noise charge (ENC) below the targeted system noise of 1000 electrons. During the few hours of main data taking time, the first tracking station was completely operational, except for a few channels and two ASICs. To allow systematic performance studies, it was operated with significantly different thresholds (between 2500 and 1200 e-) while parts of the most downstream unit in the second station could not be brought into stable operating conditions within the available time limit, and the unit therefore was kept powered off.

Periodic structures were observed in the hit time distribution of all modules. Detailed lab investigations revealed that they were caused by hits without updated timestamps due to noise in the frequency gap between slow and fast shaper sensitivity. This effect can be significantly reduced by suitable setting of the fast discriminator thresholds and by reducing noise in the relevant frequency range to the largest possible extent. As the collision reference time measurement T0 was not available in the mCBM setup, the time resolution is measured by correlating the signal in the STS with the one in the TOF detector to be below 5 ns for large amplitude signals, insensitive to signal walk delay.

Clusters are reconstructed by correlating signals from neighboring strips. A clear difference in the charge distribution of clusters measured in-spill and off-spill (background) allows to estimate the most probable value of the charge deposited by minimum ionizing particles around 24 000 e^-, which matches the expectation from the sensor bulk thickness.

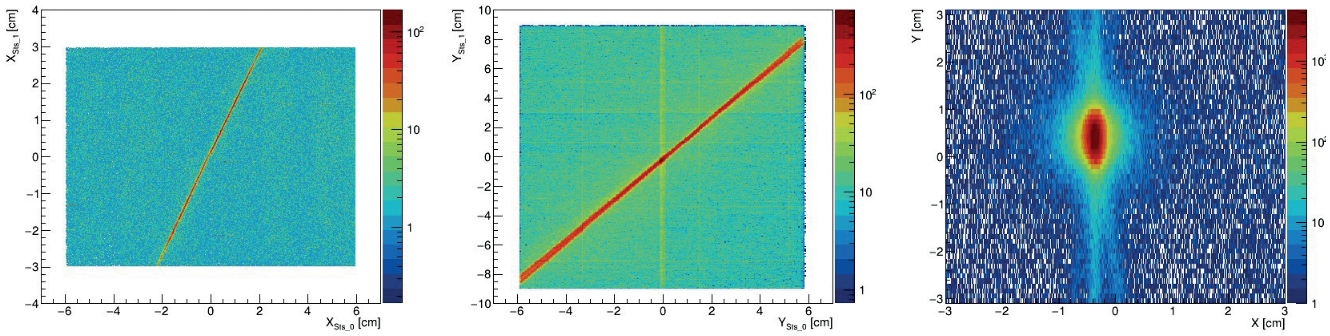

Figure 35. X,Y correlation of STS hits in Station 1 and 2. Extrapolation of vertex in the target plane.

Hits are derived from the correlation of signal clusters on the sensor p- and n-side; a space distribution is shown in Figure 35. The spatial correlation of hits in the two stations has been analyzed: first all possible combinations in a time window of 500 ns are considered, then the one with the best time coincidence is selected. Figure 35 shows the spatial correlation in X and Y coordinates for the best time coincidence. The best hit combinations are used to extrapolate tracklets to the expected vertex position in the target plane, also shown in Figure 35, right panel. Then, the position of the corresponding hit in the TOF detector is searched for. It turned out that also with the TOF, a good track correlation is observed.

The performance of mSTS detectors is still under study and optimization. However, these preliminary results make us confident that the targeted STS system can be constructed in line with the expectations.

Outlook for 2022

The next steps in the STS development will be finalization of the design of the detector infrastructure, mechanics and services resulting into the ultimate CAD model of the STS. In parallel, the assembling procedures for the larger detector structures (units and STS mainframe) will be worked out. An example of a close-to-final design of a STS detector unit is shown in Figure 36.

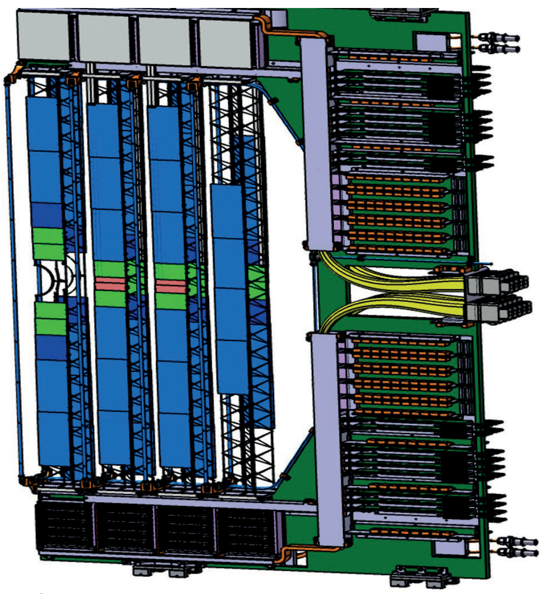

Figure 36. CAD model of a STS detector unit.

These developments will naturally require corresponding setups for unit assembly and test to be developed. The larger setups will use services (electrical power, cooling, and data links) from the C17 container placed outside the GSI Detector Laboratory building near the GSI STS integration room. Currently, these services are being installed and commissioned at the GSI campus. We expect finalization of the design of the detector components as well as the assembly and testing routines and equipment until the end of year 2022.

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- [1] Senger, A. ; Senger, P. ; CBM Collaboration: Probing Dense QCD Matter: Muon Measurements with the CBM Experiment at FAIR. Particles 4(2), 205 - 213 (2021), DOI:10.3390/particles4020019
- [2] Senger, P. ; CBM Collaboration: Astrophysics with heavy-ion beams. Physica scripta 96(5), 054002 (2021), DOI:10.1088/1402-4896/abebfe
- [3] Klochkov, V. ; CBM collaboration: The Compressed Baryonic Matter Experiment at FAIR. Nuclear physics <Amsterdam> / A 1005, 121945 (2021), DOI:10.1016/j.nuclphysa.2020.121945
- [4] Senger, P.: Probing Dense Nuclear Matter in the Laboratory: Experiments at FAIR and NICA. Universe 7(6), 171 - (2021), DOI:10.3390/universe7060171
- [5] Kumar, A. ; Agarwal, A. ; Chatterjee, S. ; et al.: Commissioning and testing of pre-series triple GEM prototypes for CBM-MuCh in the mCBM experiment at the SIS18 facility of GSI. Journal of Instrumentation 16(09), P09002 (2021), DOI:10.1088/1748-0221/16/09/P09002
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- [7] Singhal, V. ; Chatterjee, S. ; Friese, V. ; et al.: Development and implementation of a time-based signal generation scheme for the muon chamber simulation of the CBM experiment at FAIR. Journal of Instrumentation 16(08), P08043 (2021), DOI:10.1088/1748-0221/16/08/P08043
- [8] Ciobanu, M. ; Marghitu, O. ; Constantinescu, V. ; et al.: New Models of PADI, an Ultrafast Preamplifier–Discriminator ASIC for Time-of-Flight Measurements. IEEE transactions on nuclear science 68(6), 1325 - 1333 (2021), DOI:10.1109/TNS.2021.3073487

3.3 HADES

Head: Prof. Dr. Joachim Stroth (JWGU Frankfurt & GSI)
Authors: Tetyana Galatyuk (TU Darmstadt, GSI), Joachim Stroth

Figure 37. Panorama view of HADES.

HADES investigates the microscopic properties of strongly interacting matter using hadron- and ion beams provided by SIS18. In heavy-ion collisions at beam energies of around 1 GeV per nucleon densities and temperatures reached in the collision centre resemble matter expected to occur in the remnants of binary neutron star mergers. HADES also contributes uniquely to hadron physics employing proton and secondary π^- beams. In 2021 the HADES collaboration prepared the experiment setup for the proton on proton (pp) run (S518) scheduled for February 2022. To enhance the physics performance for investigation of exclusive decay channels in pp reactions, HADES decided to instrument the very forward solid angle with tracking and time-of-flight detectors (Forward Detector). In close collaboration with colleagues from the PANDA collaboration, new forward tracking detector stations were built and installed in the forward hemisphere which is not covered by the HADES spectrometer tracking. This enables precise measurement of charged particles' trajectories. To determine the momentum of the tracks in forward direction, a high-resolution RPC based TOF ($\sigma_t \approx 70$ ps) wall is placed ~7.5m downstream of the target. These forward detectors are particularly important to achieve a high acceptance for protons from hyperon decays. For time-zero measurement dedicated, newly developed sensors based on Low Gain Avalanche Detector technology will be used (see details below). The fifth sector of the electromagnetic calorimeter has been installed and equipped with dedicated readout electronics (PaDiWa-AMPs in combination with TRB3). The upgrade of the data acquisition system has been completed and a rate capability of 50 kHz for low multiplicity events has been demonstrated. To enhance the trigger purity for the low-multiplicity events, typical for p+p reactions at SIS18 energies, a fast scintillator detector system (iTOF) has been developed and installed in front of the first HADES drift chamber plane. In February 2021 a successful short test run took place with sub-sets of all new detectors in place. Besides the detector and data acquisition test, this test run was essential for studying the quality of the proton beam at maximum rigidity provided by SIS18 in slow-extraction mode. The analysis of the Ag+Ag data at 1.23 A GeV and 1.58A GeV progressed substantially and results for publications have been produced for the dielectron continuum, weak decays like , Λ-hyperon production, azimuthal anisotropy and global polarization, as well as and meson production. The writing teams are/will soon start preparing the paper drafts. A total of 13 PhD projects are connected to the data from the Ag+Ag run in 2019 and 8 PhD students are actively working on feasibility studies and detector characterization for the p+p in February 2022. Two new papers have been published in 2021: Phys. Lett. B 819 (2021), 136421 and Eur. Phys. J. A 57 (2021) no.4, 138.

Highlights in 2021

The new forward detector system

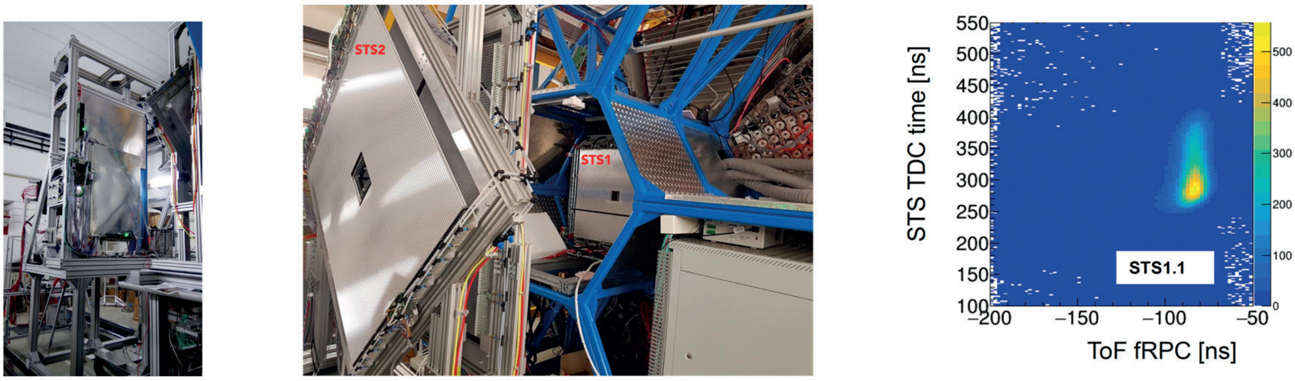

Figure 38. Left: Photograph of the front view of the two sectors of fRPC. Middle: Photograph of the back view of the two stations (STS1/2) of four double layers of self-supporting gas-filled straws. Right: Correlation of STS TDC time and time-of-flight information from fRPC from test run in February 2021.

A large fraction of the activity in 2021 was dedicated to a timely completion of the HADES detector upgrade. To enhance the physics performance for investigation of exclusive decay channels in p+p reactions, HADES decided to instrument the very forward solid angle with tracking and time-of-flight detectors. For experiments with heavy ions this solid angle is covered by a forward hodoscope for centrality and event plane determination. Particles emitted into this solid angle propagate outside of the magnetic field of the toroid and are consequently not deflected. Momentum reconstruction is accomplished here by precise time-of-flight measurement. As start- time (t0) detector serves a novel silicon detector (LGAD), placed inside the beam line vacuum, described in detail below. The stop signals are provided by a new forward RPC wall (fRPC) consisting of four identical chambers arranged around the beam axis. Each chamber contains individually shielded stacks of parallel plates (6 gaps) of dimension 22(44)mm x 22mm x 900 mm (width x depth x length). The narrower modules are positioned closer to the beam axis, and in total 32 modules are arranged in two layers in each box to provide 100% fill factor. Each module is read out from both sides to provide position information in one dimension. The rate capability was tested at the COSY synchrotron and demonstrated 100 ps time precision at rates up to 320 Hz/cm^2. This time precision, and a detection efficiency near 90%, could be maintained up to 1.5 kHz by heating the models to a temperature of 40°C. Two chambers were already installed for the test beam in February 2021 (see Figure 38, left panel). The test run revealed that the positioning close to the beam axis had to be scrutinized because of too high count-rates in the modules closest to the beam axis.

Precise tracking is accomplished by two stations of gas-filled (2 bar Ar/CO2 at 90/10 percentile) straw tube detectors built with technology developed for the PANDA forward tracking system. The straws have a diameter of 10 mm and lengths of 760 and 1250 mm for the station 1 and 2, respectively. Each tracking station (see Fig. HAD2, middle panel) contains four double stacks mounted in stereo angles of 0°, 90°, 90°, and 0° (STS1) and 0°, 90°, 45°, and -45° (STS2). Both tracking stations were operated in the test beam time in February 2021 and showed excellent performance while individual straws experienced rates up to 100 kHz (see Figure 38, right panel). The readout electronics for the straw tracking stations, as well developed for PANDA, features the PASTTREK ASIC designed by AGH Cracow and connects to the HADES TRB data acquisition system. The ASIC is also the central element of the upgrade of the drift chamber electronics currently ongoing. Simulation studies revealed that momenta can be reconstructed with a relative precision (σ) of 0.5 % and 3 % for proton momenta of 0.5 and 3 GeV/c, respectively, assuming a precision of the time measurements of 100 ps in the LGAD start and fRPC detectors and a precision of the position measurement in a double layer of 200 µm.

During the p+p beamtime, two trigger settings will be used: one will collect elastic scattering events and the second is the main physics trigger, based on the multiplicity of charged particles. In a p+p beam time it was found that a simple multiplicity reaction trigger obtained from the HADES RPC and TOF walls, in coincidence with a signal of the time-zero detector, recorded about 50% of events with no reconstructed track in the drift chamber system in the off-line analysis. To improve the main-physics trigger purity for reactions, a thin layer of organic scintillator material was introduced between the RICH and the first drift chamber plane which provides a fast charged particle multiplicity signal, which is now combined with the respective signal from the time-of-flight detectors behind the drift chamber planes. In February 2021 two sector of the iTOF were already installed and allowed a first evaluation of their influence on the purity of the reaction trigger.

Time-zero detectors based on LGAD technology

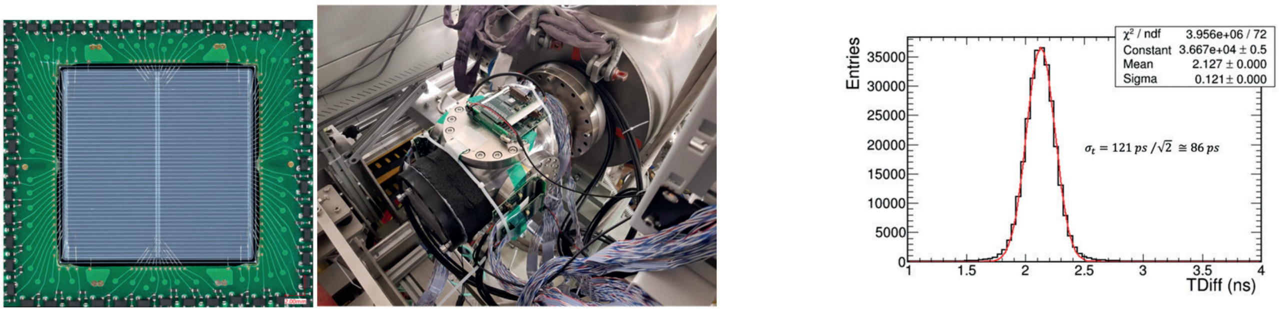

Figure 39. Left: Photograph of the 20 mm × 20 mm LGAD sensor mounted on a PCB equipped with 96 analog amplifiers. Middle: Photograph of LGADs mounted on a PCB inside the vacuum element. Right: Time precision obtained for two-channel combination utilizing PaDiWa leading-edge discriminators and a TDC system employing the FPGA-TDC concept.

To provide precise time-zero measurements, a novel detector system, employing Low-gain Avalanche Diode (LGAD) technology, has been developed and tested in beam times in Jülich and MedAustron. The detector of small dimension is placed in the beam and positioned about 1.5 m upstream from the liquid hydrogen target.

For the application in HADES teams from GSI HADES department, Detector Laboratory, and Experiment Electronics and TU Darmstadt have integrated single sensors, produced by Bruno Kessler Foundation (Trento, Italy), of dimension 2x2 cm^2 on dedicated read-out boards providing vacuum compatibility. The detector is mounted inside a beam pipe is using commercially available vacuum elements as shown in Figure 39 (middle panel).

To cope with rates of about 7.5 x 10^7 protons/s, the system is segmented such that the projected rate per strip stays below 10^6 protons/s, which is acceptable for the readout system. The maximum count rate per strip reaches 10 MHz for single (central) strips. A demonstrator was tested with a proton beam of T_{beam} = 1.92 GeV and it showed an excellent performance. The setup included the readout system utilizing NINO leading-edge discriminators and a TDC system employing the FPGA-TDC concept. The time precision reaching 47 ps has been demonstrated. The main PCB of the planned system hosts 96 amplifiers designed to work with two LGAD sensors with sizes up to 2.0 cm x 2.0 cm. Each channel was connected to two stages of amplification close to the sensor. PaDiWa discriminators, which are based on discrete components, were used for readout, while the time to digital conversion took place using FPGA based TDCs (TRB). The detector shows required radiation hardness and time precision reaching below 100 ps (see Figure 39 right panel).

In order to employ LGADs for a beam monitoring tool, the fast and scalable online calibration procedure has been developed. The LGADs setup is equipped with leading edge discriminators. Because of different signal amplitude at the input to discriminators, there is a systematic timing shift introduced by discriminators. This effect should be compensated to allow best timing precision. For this purpose Machine Learning (ML) methods was considered. This approach allows a fast, non-linear prediction for calibration parameters with much smaller calibration dataset. Achieved timing precision with Machine Learning based calibration is well in agreement with the one obtained using conventional calibration approach.

Physics results from heavy-ion runs

Significant progress in the understanding of heavy-ion collision could be achieved if the dynamics of excited baryons would be known better. The direct reconstruction of these particles is challenging as the resonances are broad and the extraction of cross section is determined by the knowledge of the underlying combinatorial background. With help of an iterative method which identifies signal and background contributions without input models for normalization constants we reconstructed correlated pion-proton pair emission from Au-Au collisions at 1.23A GeV (see Figure 40 left panel [1]). The triple differential distributions of correlated $\pi^{\pm}$-p pairs have been determined, in particular their pT-dependent line-shape parameters, multiplicity per event as a function of event centrality as well as inverse slope parameters as a function of rapidity. This data provides an important input on most abundant, yet not well-known ingredient in hitherto microscopic transport model calculations. Since for the pi-nucleon system, the s-wave scattering lengths are known, our measurement may serve as a benchmark system for studying effects that could affect the determination of scattering lengths for two-particle systems.

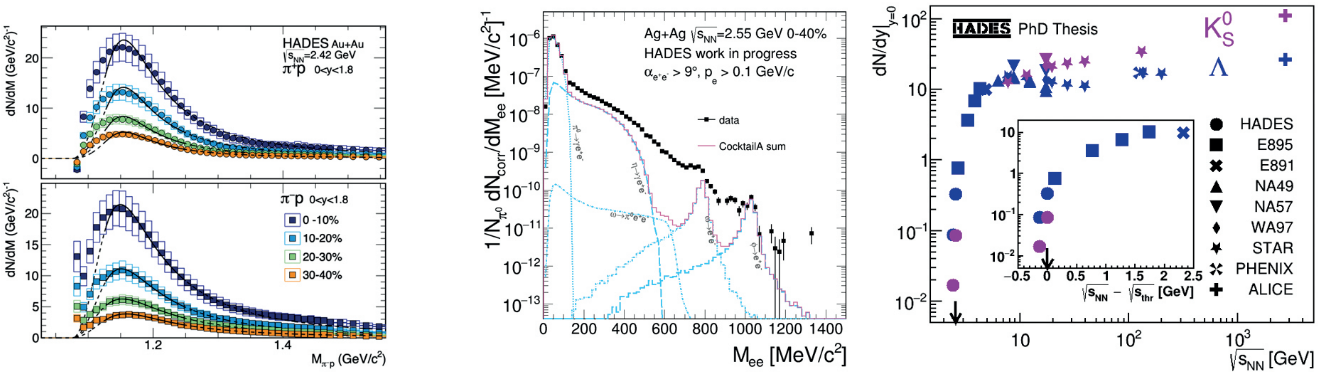

Figure 40. Left: Efficiency and acceptance-corrected invariant mass distribution of correlated π^+p (top panel) and $\pi^+ p$ (bottom panel) pairs for four centrality intervals. The mass values deduced from the invariant mass spectra are lower by more than 85 MeV/c² than the free values for Δ1232. Middle: Efficiency corrected dilepton spectrum from Ag+Ag collisions at 1.58A GeV. Right: Excitation function of K^0s and Lambda. HADES measurements in Ag+Ag at 1.58A GeV and Au+Au at 1.23A GeV are shown with red and blue solid circles correspondently.

Progress has been made on the systematic investigation of the multi-differential emission probability of dileptons in the low- and intermediate-mass range in Au-Au and in Ag-Ag collisions. The efficiency and acceptance corrected dilepton spectra have been extracted. The excess yield radiation at masses $0.2 \leq M_{ee}/(GeV/c^2) \leq 0.7$ has been extracted and allows to determine the average fireball temperature from fits to the di-electron mass in the low- and intermediate mass range assuming a Planck-like black-body radiation. The centrality, energy and system-size dependence of the extracted excess di-electron yield is being finalized and prepared for publication.

The analysis of hadron spectra, yields and azimuthal anisotropy in Ag-Ag collisions has been advanced. With help of weak-decay topology recognition enforced by a machine learning the K^0_s, Λ, Ξ^- and hypertrition yields have been successfully reconstructed and are currently prepared for publication. The excitation functions of K^0_s and Λ together with the works data are shown in Figure 40, middle panel. The analysis of charged Kaons and Φ-mesons and of charged pions is being finalized.

Recently the Identity Method was developed further and integrated into the HADES analysis chain to perform the event-by-event fluctuation analysis of protons as well as light nuclei for the first time. The method circumvents in a probabilistic manner the overlapping detector signals used for particle identification. The implementation also contains the traditional approach based on cut-based particle identification. The Au-Au data of HADES at projectile kinetic energy of 1.23A GeV and the corresponding simulated events were analysed using both methods.

Outlook for 2022

A four weeks production beam time is scheduled for February 2022 to investigate p+p reactions at 4.5 GeV beam energy. We expect to run at 40-50 kHz reaction rate with 50% dead time of the data acquisition. Depending on the actual beam on target time, including the duty cycle of the SIS18 in slow extraction mode, we hope to record 30 billion events. The main focus of the beam time is the first observation of radiative decays of excited hyperon states in the time-like region. The data analysis of the Ag-Ag beam time has far progressed, and many results are obtained and ready for publication. Among these results are the dilepton continuum radiation ranging up the vector meson, inclusive charged kaon and production, weak decays of strange hadrons also including a measurement of the hyper-triton lifetime.

Selected publications of 2021

- [1] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al.: Correlated pion-proton pair emission off hot and dense QCD matter. Physics letters / B 819, 136421 (2021), DOI:10.1016/j.physletb.2021.136421
- [2] Adamczewski-Musch, J. ; Belyaev, A. ; Blanco, A. ; et al.: Production and electromagnetic decay of hyperons: a feasibility study with HADES as a phase-0 experiment at FAIR. The European physical journal / A 57(4), 138 (2021), DOI:10.1140/epja/s10050-021-00388-w
- [3] Salabura, P. ; Stroth, J.: Dilepton radiation from strongly interacting systems. Progress in particle and nuclear physics 120, 103869 (2021), DOI:10.1016/j.ppnp.2021.103869

4. Research of the NUSTAR Departments

Coordination: Prof. Dr. Christoph Scheidenberger (JLU Gießen, GSI)
Author: Christoph Scheidenberger

The NUSTAR collaboration pursues one of the four major scientific directions of GSI and FAIR: nuclear structure, nuclear astrophysics, reactions and superheavy element research. The NUSTAR departments of GSI and HIM (Helmholtz Institute Mainz) are integral part of the NUSTAR Collaboration and participate in and contribute to the experiments with intense stable beams and with exotic nuclei at GSI-FAIR. They are also part of the research topic “Cosmic Matter in the Laboratory” of the Helmholtz program “Matter and the Universe”. The NUSTAR mid-term strategy aims at the exploitation of new high-level scientific opportunities at the existing GSI accelerator facility using the novel equipment for FAIR, which is already available, and a continuous transition from GSI to FAIR as soon as the Super-FRS becomes available. The main research instruments and experimental areas at GSI-FAIR are located at SHIP/SHIPTRAP, TASCA, FRS, ESR-Cryring and R3B in Cave-C. The respective research groups of GSI and HIM perform, integrated in the NUSTAR Collaboration, a world-leading research program addressing burning scientific questions.

The year 2021 was very busy due to the continuation of the vivid experiment program at the UNILAC and the continued FAIR Phase-0 experiments at SIS-18. Despite the prevailing pandemic, the experiments could be performed almost according to the originally planned schedule, although travel and participation of collaborators from abroad was still severely restricted; again, this lead to increased remote access of collaborators, remote control of their complex equipment on the GSI campus and tremendous efforts for making a large variety of contributions to the running experiments from a distance; the collaborative spirit continued in a really excellent manner. The FAIR Phase-0 experiments allow the collaboration to obtain important and unique science results, to test the complicated FAIR detector equipment under realistic conditions, to master the organization of complex collaborative processes, and to train graduate students and young post-docs on the way to NUSTAR@FAIR. Some results are displayed in the following sections.

4.1 FRS/SFRS

Head: Prof. Dr. Christoph Scheidenberger (JLU Gießen & GSI)
Author: Author/s: Vratislav Chudoba (Univ. Opava), Timo Dickel, Andrey Fomichev (JINR-Dubna)*, Bernhard Franczak, Hans Geissel (GSI, JLU Gießen), Emma Haettner, Christine Hornung, Daria Kostyleva, Natalia Kuzminchuk, Ivan Mukha, Wolfgang R. Plaß (GSI, JLU Gießen), Sivaji Purushothaman, Takehiko Saito (GSI, RIKEN), Christoph Scheidenberger, Yoshiki Tanaka (RIKEN)
* The results presented here are from work carried out before 24. February 2022.

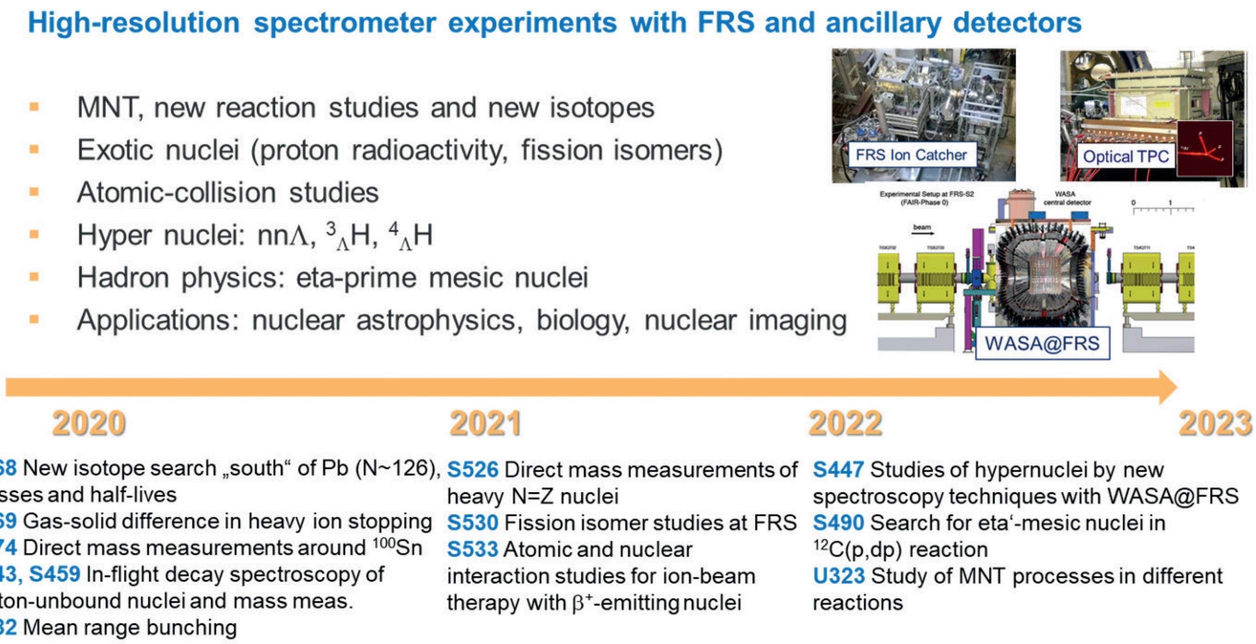

Figure 41. Overview of scientific program, physics goals and pilot experiments of the Super-FRS Experiment Collaboration that were already performed in 2020 and 2021, respectively, and that are planned for 2022.

The FRS experiments are performed in close cooperation with scientists from many different countries and institutes in the framework of the Super-FRS Experiment Collaboration (Super-FRS EC), which is one of the scientific branches of the NUSTAR Collaboration at FAIR. The experiments address a variety of science topics in the fields of atomic, nuclear and hadron physics and applications. The connecting element is the scientific topicality, the high momentum resolution capability of the FRS, and the world-wide unique feature are relativistic beam energies reaching up to 18 Tm magnetic rigidity for all elements (from protons to uranium). The physics program and mid-term plans are depicted in Figure 41.

Next to the spectrometer experiments, the FRS is the backbone of the experiments of the NUSTAR Collaboration with exotic nuclei at SIS18, as will be the Super-FRS at SIS18/100 at FAIR. Therefore, training of the next-generation of scientists is vital to perform experiments in future. Accordingly, a large effort was launched and the NUSTAR Beam Team was implemented with the goal to train the members of the Super-FRS project group and several sub-collaborations of the NUSTAR Collaboration. The experiments were performed jointly in the first half of 2021 using 6 different primary beams addressing more than 40 different regions of interest in the Chart of Nuclei. Several new ion-optical modes of the FRS were applied, among them the newly developed high-transmission mode [1] and the new mode connecting the medical Cave M with the FRS (see below). Overall 10 different ion-optical modes of the FRS were used, which were specifically tailored to optimize the individual experiment needs. The newly implemented concept of using pre-assembled platforms for the experimental setups at the major focal planes of the FRS was applied. In view of the extremely tight beamtime schedule (15 different experiments during 95 beam days within 131 days) this was a necessity and was proven to be quite helpful for a quick and reliable change-over from one experiment to the next. The photograph (Figure 42) shows the members of the NUSTAR Beam Team after the end of the beamtime period 2021.

[1] E. Haettner et al., Nucl. Instr. Meth Phys. Res. 463, 455-459 (2020)

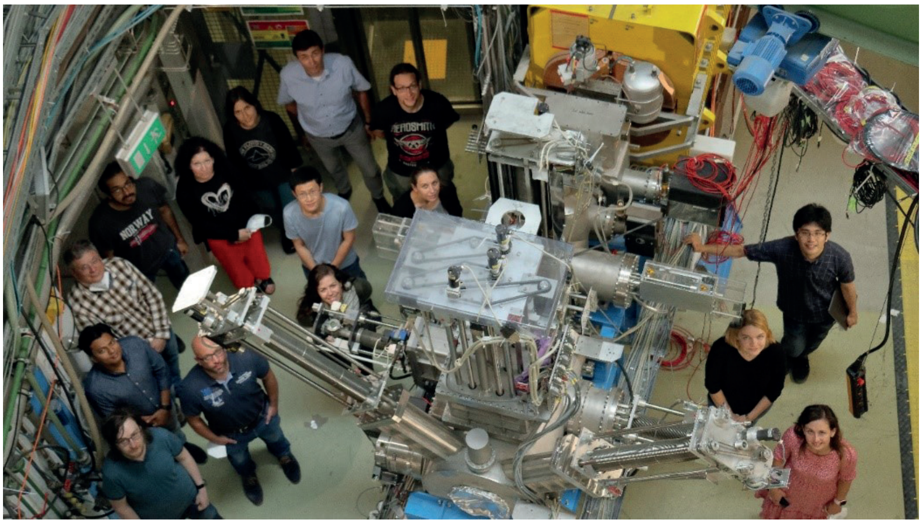

Figure 42. Area view of the central focal plane of the FRS with some experiment participants 2021.

Highlights in 2021

Production and study of positron emitters for ion-beam therapy

The use of positron emission tomography (PET) imaging as a technique for range verification in stable ion beam therapy has been extensively investigated over the last three decades. The main uncertainties come from the non-matching activity peak compared to the Bragg peak of the treatment beam and the low PET counting statistics. In the case of radioactive ion beam therapy, however, the range verification is straightforward since the predominant source of positron emitters are the ions of the therapy beam themselves. Following the pioneering work at Lawrence Berkeley National Laboratory, USA, and further investigations at HIMAC, Japan, a new European initiative on the biomedical applications of radioactive ion-beams (BARB) has been launched at GSI in 2021 [Bos21]. It aims at the pre-clinical validation of in-vivo beam visualization and ion-beam therapy with positron-emitting isotopes of carbon and oxygen using a small animal irradiation technique. The FRS group and the Super-FRS Experiment Collaboration make significant contributions and pursue several scientific studies within the BARB initiative in collaboration with Biophysics within APPA.

For these studies and for efficient transport of the PET-isotopes to the medical Cave M, a new ion-optical mode has been developed, which accounts for the large phase space of the fragmentation products and the properties of the connecting beamline between the final focus of the FRS and the entrance of Cave M (the layout of this beamline is adjusted to the small emittances of primary beams from SIS18). The beamline and this new ion-optical mode was used successfully for the first time with PET isotopes (^{14}O, ^{15}O) for biophysics experiments in Cave M (see APPA contribution to this report).

At the FRS itself high-quality, high-statistics in-beam PET images were produced with the in-flight separated ^{10}C, ^{11}C, ^{14}O, and 15O, exploiting the higher beam intensity available at the final focus of the fragment separator FRS. The positron emitters were implanted into a PMMA phantom (plexi glass) with therapy-relevant energies and imaged using a dual-panel PET scanner provided by the University Medical Center Groningen, the Netherlands. Figure 43 shows a typical particle identification plot as obtained for ^{10}C and the image of ^{10}C ions after implantation into the PMMA; the incident energy was about 150 MeV/u and the calculated range is 39 mm. The relationship between the PET image quality and deposited dose during ion beam therapy with positron-emitting nuclei is presently investigated. The unprecedented statistics will allow for specific studies and for benchmarking this novel approach.

In addition, the nuclear interaction and charge-changing cross-sections of ^{11}C, ^{10}C, ^{15}O, and ^{14}O in carbon, PE, Be, and water targets were measured at therapy relevant energies. These cross-sections of therapy-relevant ions in tissue or tissue-equivalent materials (e.g. water) are important ingredients of Monte Carlo transport codes (e.g. FLUKA and GEANT4), which are used in the context of treatment planning for ion beam therapy with the above-mentioned positron emitters.

[Bos21] D. Boscolo et al., Front. Oncol., 11, 737050 (2021).

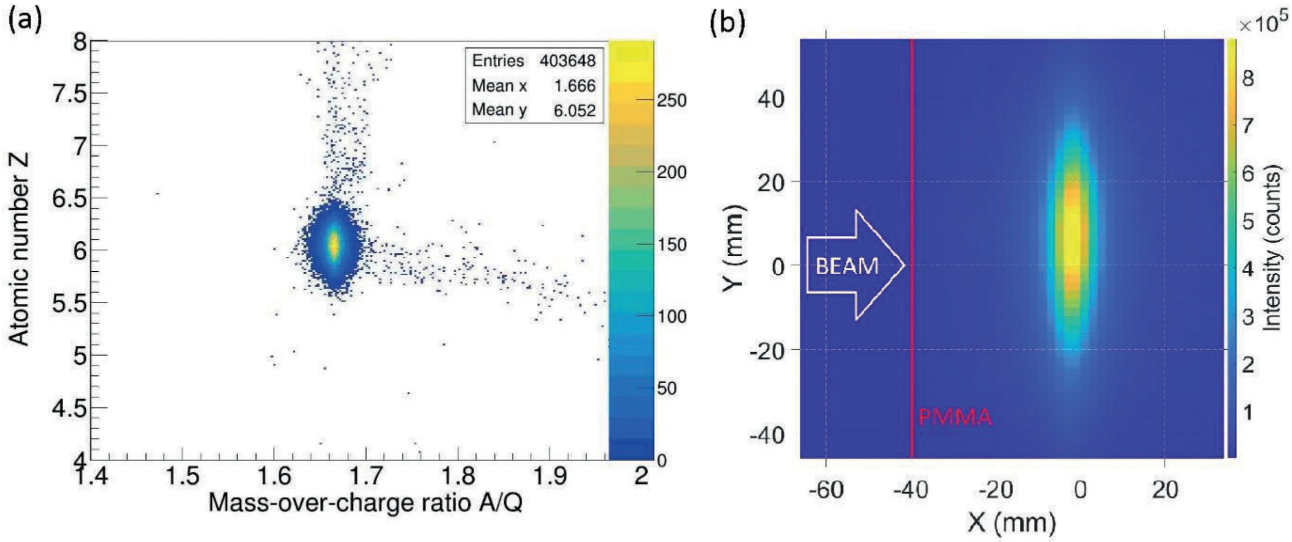

Figure 43. (a) Particle identification plot showing the $^{10}C^{6+}$ ions produced by the FRS. The beam purity is in excess of 99 %. (b) PET image of ^{10}C ions implanted into PMMA, with an energy of about 150 MeV/u and an expected range of 39 mm. The image is corrected for the scanner's sensitivity and attenuation in the PMMA and comprised around 2×10^8 decay events.

Direct mass measurements of exotic nuclei

The total binding energy of a nuclide, which is reflected by its mass, is often one of the first measurable quantities of an atomic nucleus after its discovery. It provides hints to nuclear structure properties far off stability, their changes along isotopic, isotonic or isobaric chains, pairing and shell effects, and it allows to determine the limits of stability. In many cases, the experimental access to the nuclei of interest or in an isomeric state is not limited by the low production rate and corresponding yields, but by an overwhelming (e.g. isobaric) background which obscures the observation of rare species. There are several, different approaches to cope with this challenge.

At the FRS Ion Catcher a special detector has been installed recently, which allows to improve the signal-to-noise ratio by tagging the alfa-decay of the detected ions in addition to the time-of-flight mass measurement. This so-called alfa-TOF detector has been developed by collaborators from KEK, Japan, and was used for the first time in FAIR Phase-0 experiments in 2021. Another route is provided by high-resolution mass separation, which is pursued world-wide e.g. with the recently developed multiple-reflection time-of-flight mass spectrometers (MR-TOF-MS), to overcome this difficulty. Based on the developments at the FRS Ion Catcher and at the JLU Gießen, the group has built an MR-TOF-MS for the TITAN experiment at TRIUMF, Vancouver, Canada. The device is in routine operation since 2017 and works as high-resolution mass separator ($m/\Delta m \approx 100{,}000$) and mass spectrometer ($\delta m/m \approx 2\cdot10^{-8}$) [Rei21]. It extends the reach of mass measurements by several mass units further away from stability, and is most frequently used for mass measurements at TITAN, as has been documented in several publications [Izz21, Muk21, Pau21].

Recently, the novel method of re-trapping was developed and used for the suppression of isobaric background, which allows for mass separation and simultaneously for high-precision direct mass measurements [Bec21]. Corresponding spectra are shown in Figure 44. A highlight feature of recent experiments, that were performed using this novel scheme, is the extension and study of the isomeric chain in the even-Z isotonic nuclei with neutron number N=81. The stability of the excitation energy over than long chain is unique on the nuclear chart and can be understood in detail for the first time by state-of-the art mean filed calculations (see Figure 44):

[Rei21] M.P. Reiter et al., Nucl. Instr. Meth. A1018, 165823 (2021)
[Izz21] C. Izzo et al., Phys. Rev. C 103, 025811 (2021)
[Muk21] I. Mukul et al., Phys. Rev. C 103, 044320 (2021)
[Pau21] S. F. Paul et al., Phys. Rev. C 104, 065803 (2021)
[Bec21] S. Beck et al., Phys. Rev. Lett. 127, 112501 (2021)

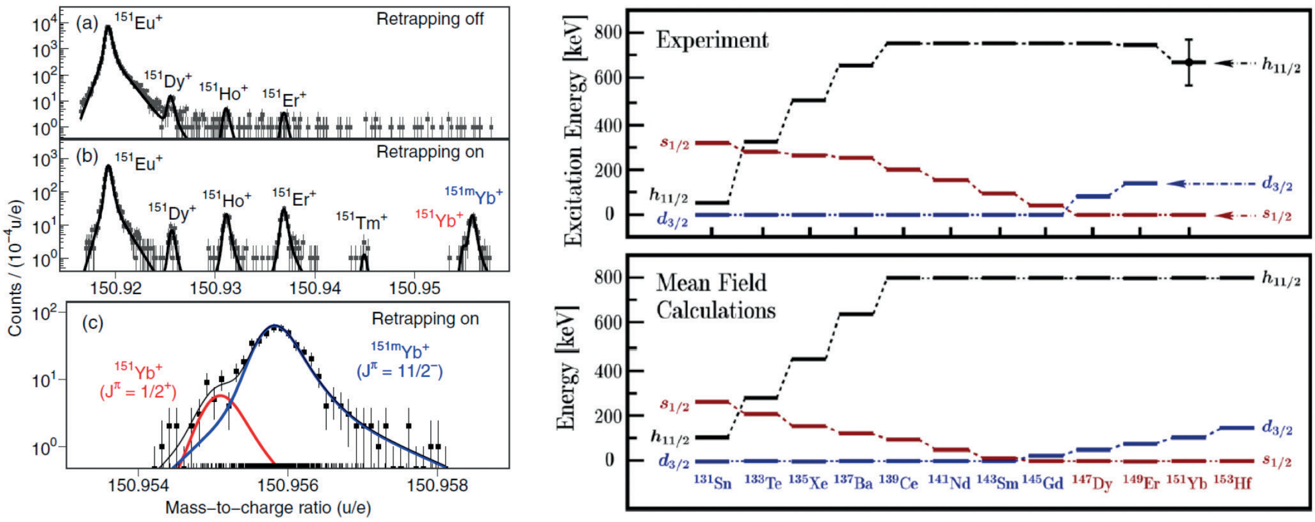

Figure 44. (left) Mass spectra of A=151 isobars obtained with the MR-TOF-MS at the TITAN facility in TRIUMF, Vancouver, Canada. The time-of-flight mass spectra are obtained without (top) and with (centre) retrapping of time-of-flight mass-separated ions: the timing is optimized for efficient retrapping of ^{151}Yb and suppression of other isobaric contaminants (one should note the different intensity scales). The spectrum at the bottom shows the ground state and the isomeric state of ^{151}Yb. After the retrapping, the time-of-flight of the Yb ions is about 8 ms. (right) Measured excitation energies of isomers in the even-Z N=81 isotones from ^{131}Sn up to 151Yb (top); their $h_{11/2}$ excitation energies are constant from Ce to Yb. Corresponding results from mean-field calculations (bottom) with a universal parametrization of the Woods-Saxon Hamiltonian; from Nd to Hf the filled proton levels are nearly degenerate. For details see [Bec21].

Experiments with EXPERT prototype detectors and related developments

The EXPERT setup is under development and parts of it are already in current use for experimental studies of exotic, unbound nuclear systems by measuring correlations of their decay products: Exotic Particle Emission and Radioactivity by Tracking. The experiments use the first half of the FRS for production and separation of radioactive beams and its second half as a high-resolution spectrometer for the reaction and decay products. The short-lived nuclei of interest, some of them located several mass units beyond the proton dripline, are produced at the centre of the FRS by impinging the separated radioactive beams on a secondary target, and trajectories of the in-flight-decayed products are tracked, which allows to derive e.g. their half-lives and resonance energies. A similar experimental scheme can be applied in future at the Super-FRS.

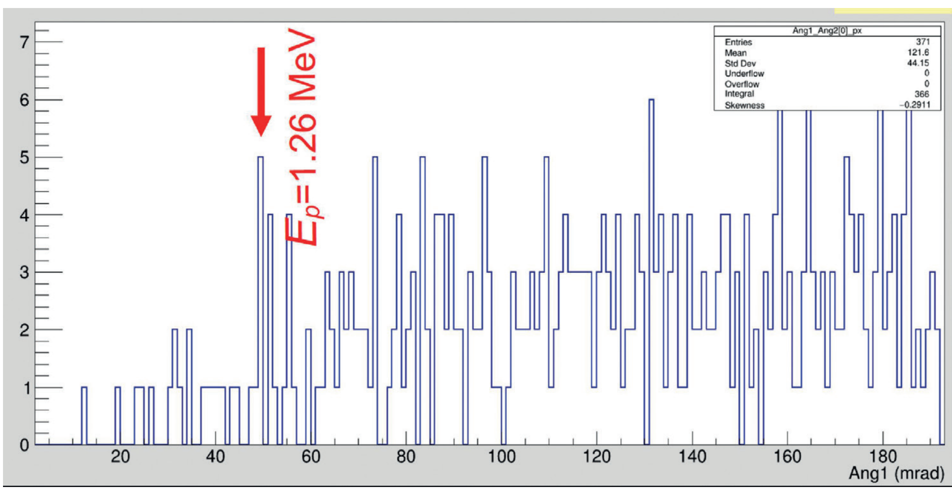

Figure 45. Angular correlation of ^{69}Se nuclei and protons from 1p-decays of ^{70}Br* (histogram, preliminary data). The peak at 1.26 MeV (indicated by the red arrow) points to a previously unknown state in ^{70}Br at 3.54 MeV.

First pilot experiments with EXPERT prototype detectors have been performed in two FAIR Phase-0 experiments S443 and S459, which aimed at nuclear-structure spectroscopy of proton-unbound ^{69}Br and ^{73}Rb nuclei. These nuclei are of interest because of their particular role in the synthesis of chemical elements in the Universe, which proceeds via the rapid-proton-capture process that drives thermonuclear runaways in type-I X-ray bursts in binary-star systems. About 10^6 projectiles of ^{70}Br and ^{74}Rb impinged on the secondary ^{12}C target at the central focal plane of the FRS. The resulting

^{69}Br and ^{73}Rb nuclei decayed in-flight, and their 1p-decay products were identified and tracked. A by-product of the experiment, namely the inelastic scattering of ^{70}Br followed by its 1p-decay to ^{69}Se, yields preliminary data on the previously-unknown spectrum of ^{70}Br, which is shown in Figure 45. As only 5% of the available statistics are analysed, we expect reliable spectroscopy results for the isotopes of interest (^{69}Br, ^{73}Rb) at the end of the year 2022.

For forthcoming EXPERT experiments, new silicon micro-strip detectors ("FOOT", active area 100 cm^2) for tracking of protons and heavy ions have been developed and built. The corresponding electronics, front-end boards, digitising and FPGA-based steering modules allow up to five times higher counting rates. Test experiments will be performed in 2022 jointly with the R3B collaboration.

Preparations for experiments using WASA@FRS

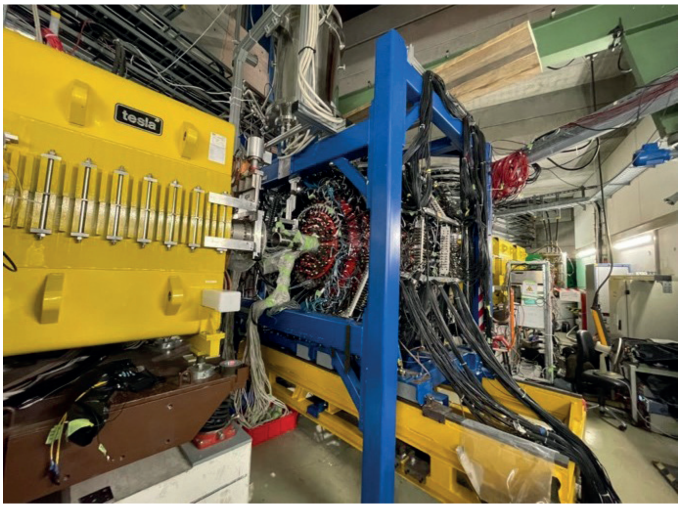

Figure 46. The WASA detector with newly developed ingrdients installed at the central focal plane of the fragment separator FRS.

The preparation of the WASA@FRS experiment campaign, that is planned for February and March 2022, has continued at GSI by the FRS/SFRS group together with the Super-FRS Experiment Collaboration. The WASA apparatus, including the superconducting solenoid magnet and its associated cryogenic system, the the iron yoke with the integrated CsI calorimeter and the inner drift chamber, the so-called MDC, has been mounted at the middle focal plane of the FRS. Several of its subsystems, including electronics and read-out systems, have been upgraded and were adapted to the specific needs of the forthcoming experiments. All fiber detectors, which were developed by the High Energy Nuclear Physics Laboratory (HENP) at RIKEN and Osaka University, were shipped to GSI and have been integrated in WASA. The new plastic scintillator barrel detector, the PSB, developed by the Meson Science Laboratory at RIKEN, was also shipped to GSI and mounted inside the WASA superconducting solenoid magnet. The small plastic hodoscope for measuring beam particles has also been developed by the HENP at RIKEN and mounted in front of the WASA detector. Two new plastic end-cap detectors, so-called PSFE and PSBE, have been developed by the HENP at RIKEN and Lanzhou University and integrated in the WASA detector system. All detectors have been commissioned with cosmic rays and beta-radiation sources. Figure 46 shows a photograph of the WASA detector mounted at S2, the central focal plane of the FRS. The cryogenic system for cooling the WASA superconducting magnet includes a 3,000 liter liquid helium (LHe) dewar and it is installed on the concrete shielding roof on top of and near S2. The superconducting magnet has been commissioned successfully at 4 K and excited to 1 T field strength. The development of silicon vertex detectors is in progress at CSIC-Madrid and will be finalized before the experiments.

A review paper discussing new directions of hypernuclear physics, including the WASA@FRS hypernuclear experiment, has been published as a perspective article in Nature Reviews Physics [Sai21]. Two GSI press releases were launched related to this article and the WASA@FRS project.

[Sai21] T.R. Saito et al., Nat. Rev. Phys. 3, 803–813 (2021).

Outlook for 2022

The commissioning of WASA@FRS will be performed and first experiments using the high momentum resolution capabilities of the FRS spectrometer are scheduled for February and March 2022. Key activities are the search for eta-prime mesic nuclei and the study of light hypernuclei with emphasis on the question of the existence of a bound nnΛ-system and the lifetime of hypertriton.

In the first half of the year 2022, the FRS department and the Super-FRS Experiment Collaboration will continue to support the NUSTAR FAIR Phase-0 experiment program. The further development of the NUSTAR Beam Team for experiments with relativistic radioactive beams is an important activity of the group and will be pursued together with members of the HISPEC/DESPEC and R3B collaborations, respectively. This activity proceeds hand in hand with the training of a new generation of experimentalists for the Super-FRS of FAIR.

In the second half of the year, the department will concentrate its efforts on the full exploitation of the data recorded in experiments of the Super-FRS Experiment Collaboration in years 2020 and 2021. On the technical side, all 54 mechanical drives of FRS will be replaced by the new FAIR stepper motors and related controls and the vacuum control system will be refurbished. On the development side, the department will concentrate on further tests of EXPERT detector components (e.g. first pixel-detectors based tracking station with an active area of 100 cm2 will be completed and tested with different beams at Krakow, Poland, at CERN and at FZ Jülich), and the construction of the cryogenic stopping cell CSC for the Super-FRS at FAIR.

Selected publications of 2021

- [1] Bogdanov, O. V. ; Pivovarov, Y. L. ; Tukhfatullin, T. A. ; et al.: Half-wave-crystal channeling of relativistic heavy ions at Super-FRS GSI/FAIR. Nuclear instruments & methods in physics research / B 486, 22 - 27 (2021), DOI:10.1016/j.nimb.2020.09.022
- [2] Boscolo, D. ; Kostyleva, D. ; Safari, M. J. ; et al.: Radioactive Beams for Image-Guided Particle Therapy: The BARB Experiment at GSI. Frontiers in oncology 11, 737050 (2021), DOI:10.3389/fonc.2021.737050
- [3] Beck, S. ; Kootte, B. ; Dedes, I. ; et al.: Mass Measurements of Neutron-Deficient Yb Isotopes and Nuclear Structure at the Extreme Proton-Rich Side of the N = 82 Shell. Physical review letters 127(11), 112501 (2021), DOI:10.1103/PhysRevLett.127.112501
- [4] Mardor, I. ; Andrés, S. A. S. ; Dickel, T. ; et al.: Mass measurements of As, Se, and Br nuclei, and their implication on the proton-neutron interaction strength toward the N = Z line. Physical review / C 103(3), 034319 (2021), DOI:10.1103/PhysRevC.103.034319
- [5] Reiter, M. P. ; Andrés, S. A. S. ; Bergmann, J. ; et al.: Commissioning and performance of TITAN's Multiple-Reflection Time-of-Flight Mass-Spectrometer and isobar separator. Nuclear instruments & methods in physics research / A 1018, 165823 (2021), DOI:10.1016/j.nima.2021.165823
- [6] Saito, T. R. ; Dou, W. ; Drozd, V. ; et al.: New directions in hypernuclear physics. Nature reviews 3(12), 803 - 813 (2021), DOI:10.1038/s42254-021-00371-w
- [7] Winfield, J. S. ; Geissel, H. ; Franczak, B. ; et al.: Ion-optical developments tailored for experiments with the Super-FRS at FAIR. Nuclear instruments & methods in physics research / B 491, 38 - 51 (2021), DOI:10.1016/j.nimb.2021.01.004

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, the properties of astrophysical objects like neutron stars, as well as nucleosynthesis processes in stars, star explosions, and neutron-star mergers by measurements of reactions with short-lived nuclei. A start version of the FAIR R^{3}B experiment has been installed in Cave C at GSI while completion of the detector construction is still ongoing. For the FAIR Phase-0 production beam-time in 2021, the setup has been further completed by adding a high-rate tracking system in vacuum based on fibre detectors. For the foreseen beam time in 2022, the preparation of further advancements of the detection systems have been started, in particular, a new target-recoil detector based on Foot Si micro-strip detectors, and a large-area RPC detector for proton time-of-flight measurement after GLAD.

Highlights in 2021

Experiments with stable nuclei at RCNP and JINR: development of the R^{3}B program for FAIR

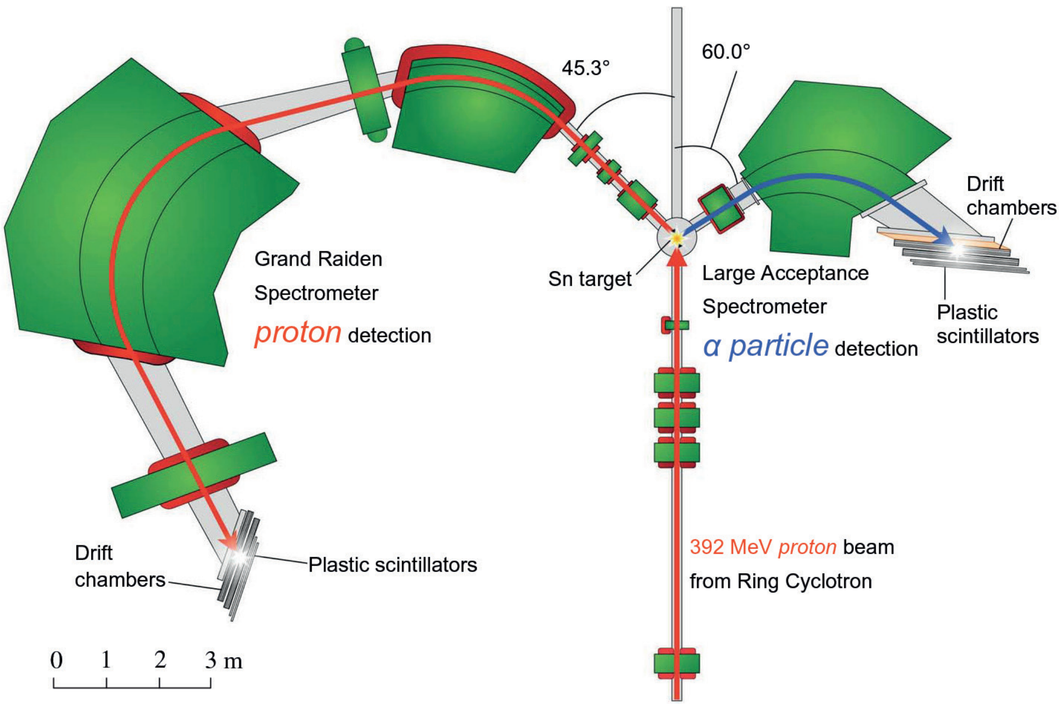

Figure 47. Schematic illustration of the experimental setup to quasi-free knockout reactions on Sn isotopes at RCNP. Scattered protons and particles are measured in coincidence at quasi-free kinematics with the Grand Raiden Spectrometer and the Large-Acceptance Spectrometer, respectively. Figure reprinted from J. Tanaka, Zaihong Yang, S. Typel et al., Science 371, 260 (2021) with permission.

In order to prepare and to complement the R^{3}B physics program, experiments with stable nuclei at different accelerator laboratories have been carried out. At the RCNP at Osaka University, Japan, an α knockout experiment has been performed in order to study α clustering at the surface of heavier nuclei. It is known from nuclear-matter calculations, that light clusters freeze out at low densities. Theoretical generalised relativistic density functional (gRDF) calculations by Stefan Typel (GSI) [Phys. Rev. C 89, 064321 (2014)] predicted the formation of α clusters at low density at the surface of nuclei if both neutron and proton densities are of similar size and magnitude at the surface. For neutron-rich nuclei, a neutron skin is developed which hinders cluster formation. Such a beyond mean-field effect can be important for extracting information on the equation of state of neutron-rich matter from nuclear observables like the neutron-skin thickness. Its determination for neutron-rich nuclei is a central program of R^{3}B. The experiment used a 392 MeV proton beam to measure the (p,pα) reactions on highly-enriched targets of Sn isotopes covering the mass range from 112 to 124. The proton and the α particle have been measured in coincidence with high resolution in quasi-free kinematics. The setup with the two spectrometers is shown in Figure 47.

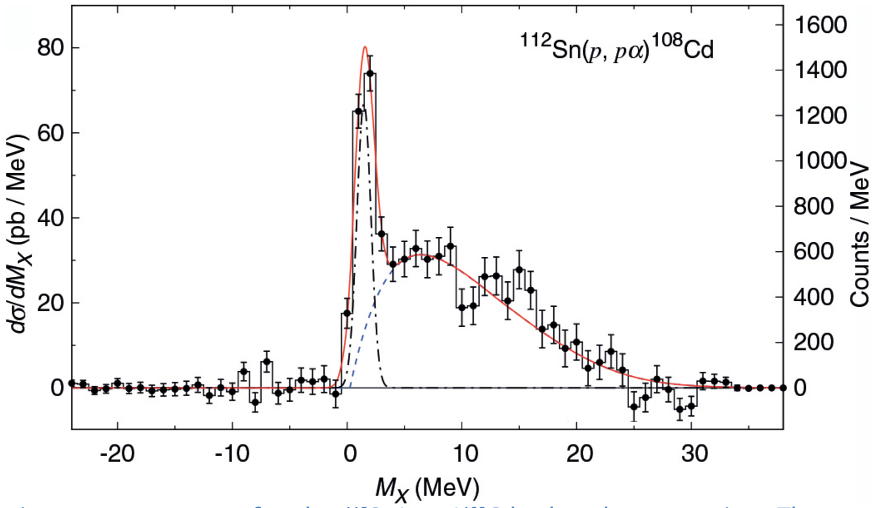

Figure 48. Missing-mass spectrum for the ^{112}Sn(p,pα)^{108}Cd a-knockout reaction. The peak at around 2 MeV corresponds to the population of the ^{108}Cd ground state after knockout of an α particle from ^{112}Sn. Figure reprinted from J. Tanaka, Zaihong Yang, S. Typel et al., Science 371, 260 (2021) with permission.

The missing mass is reconstructed from the proton and α momenta and is shown in Figure 48 for the ^{112}Sn(p,pα)^{108}Cd reaction. A clear peak is visible at the expected energy for knockout to the ground state of ^{108}Cd, which clearly corroborates the formation of α clusters at the surface of the nucleus. The cross section has been measured along the stable tin isotopes up to mass 124 showing a continuous decrease with neutron excess, reaching around a factor of two for ^{124}Sn compared to ^{112}Sn. This result is in remarkable agreement with the theoretical gRDF calculation, predicting a reduced clustering when a neutron skin develops for neutron-rich nuclei. A measurement of short-lived nuclei is foreseen at R3B for FAIR Phase-1 to study the possible consequences of such an effect on extracting the density dependence of the symmetry energy from a measurement of neutron-skin thicknesses. The clustering at the surface of nuclei might also be key for the quantitative understanding of the preformation probability in the α decay of heavy nuclei. At R^{3}B, neutron-rich α emitters can be studied to shed light on this long-standing issue.

A recent experiment at JLAB investigating short-range correlated nucleon pairs (SRC) in nuclei systematically, has suggested a dominance of neutron-proton SRC pairs, and a strong dependence of SRC as a function of neutron-to-proton N/Z ratio in nuclei, implying consequences on the properties of neutron-rich nuclei and neutron-rich nuclear matter [M. Duer et al., Nature 506, 617-621 (2018)]. Since experiments with electron beams are limited presently to stable nuclei, the N/Z dependence and the mass dependence of the SRC signal could not be disentangled in the experiment at JLAB. At R3B, a program is foreseen for FAIR Phase-1 to quantify SRC in short-lived neutron-rich nuclei along isotopic chains, and in different mass ranges. This program will enhance the sensitivity and will allow for clear separation of the N/Z dependence from mass- and size effects. As a first step towards this goal, a system as close as possible to a previously measured system has been chosen for a (p,2p) measurement in inverse kinematics using a high-energy beam of ^{12}C at the JINR in Dubna, Russia. The high beam momentum of 4 GeV/c per nucleon allows for a measurement in a similar momentum-transfer region as the high-energy electron JLAB experiment. The old LAND detector from GSI has been used to detect the recoil neutrons from SRC pairs, and has been integrated in the BM@N setup at the JINR.

The experiment clearly could demonstrate the power of the inverse-kinematics technique to study high-energy reactions. Besides the missing energy E_{miss} and the missing momentum, derived from the measurement of the two scattered protons, the residual fragment can be identified and its momentum measured. This allows for extracting a clean data sample with one-step reactions, since secondary reactions caused by final-state interactions (FSI) will destroy the fragment and thus can be be largely suppressed. This can be seen in Figure 49 where the opening angle between the two scattered protons and E_{miss} is shown. The left part shows this distribution without condition on the final state, while the right part displays the same distribution requiring an identified ^{11}B nucleus in the final state. The underlying background caused by more-step reactions is suppressed, and the two regions corresponding to quasi-elastic (QE) and quasi- inelastic (IE) implying the excitation of one proton, are more clearly visible and distinguishable. The effect can also be seen in the lower parts, where the projections on the missing mass show a much better signal-to-background ratio in the QE peak. Since the SRC signature falls into a kinematical region with relatively large contributions from FSI, the inverse kinematics experiment planned at R3B will have a big advantage compared to conventional experiments.

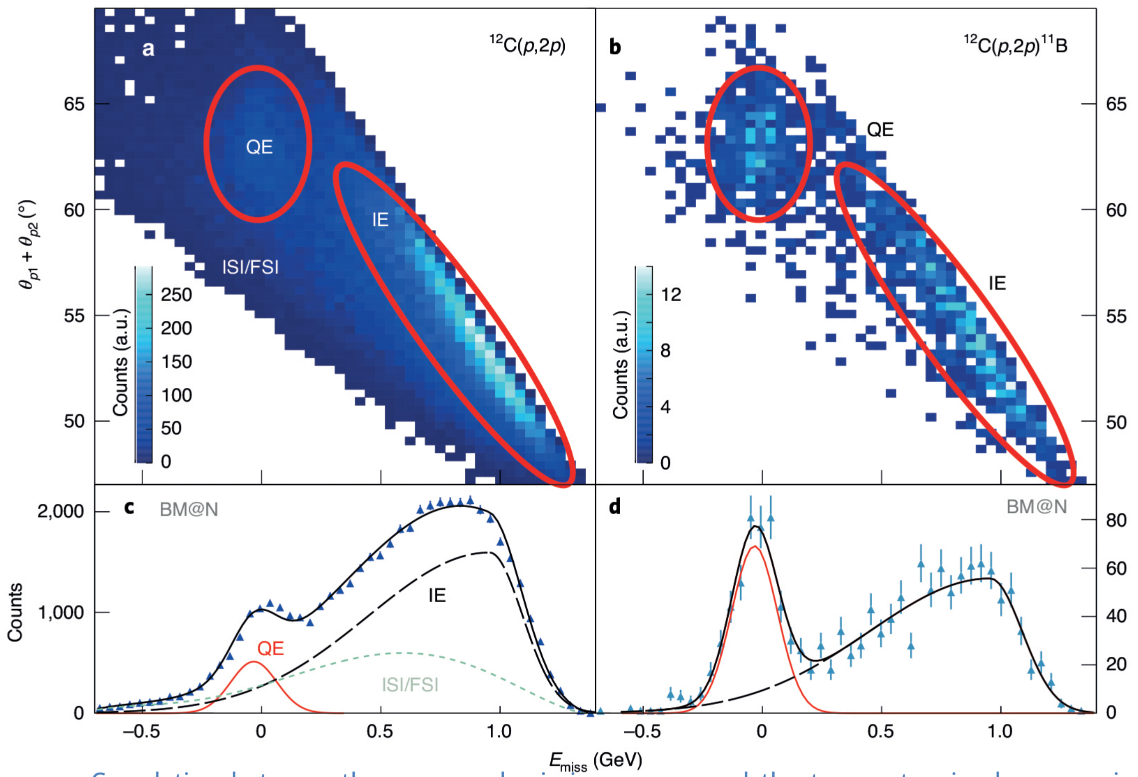

Figure 49. Correlation between the measured missing energy and the two-proton in-plane opening angle for inclusive (left) and for the reaction requiring an identified ^{11}B nucleus in the final state. Figure reprinted from M. Patsyuk et al., Nature Physics 17, 693 (2021) with permission.

For the $^{12}C(p,2p)^{10}B$ channel, also SRC pairs have been identified.The coincident detection of the A-2 fragment again provides suppression of background due to FSI, and provides additional information with the momentum distribution of the fragment. This distribution reflects the CM motion of the correlated pair in the nucleus. In Figure 50, the two insets illustrate the relative momenta of the SRC pair, and the reconstructed angles between them as shown by the experimental distributions in the two angles. While the angular distribution between the direction of the relative momentum in the SRC pair is not correlated with the pair CM momentum (flat distribution on the right), the momenta of the nucleons in the SRC pair show a clear back-to-back correlation as expected for short-range correlated nucleons. In this experiment, SRC pairs have been identified for the first time in an inverse-kinematics experiment, demonstrating the feasibility of the method to study the properties of SRC pairs in short-lived nuclei. As the next step, an experiment is being prepared at R^{3}B to measure the same reaction with ^{12}C, but also for the neutron-rich ^{16}C for direct comparison. The experiment is scheduled for May 2022.

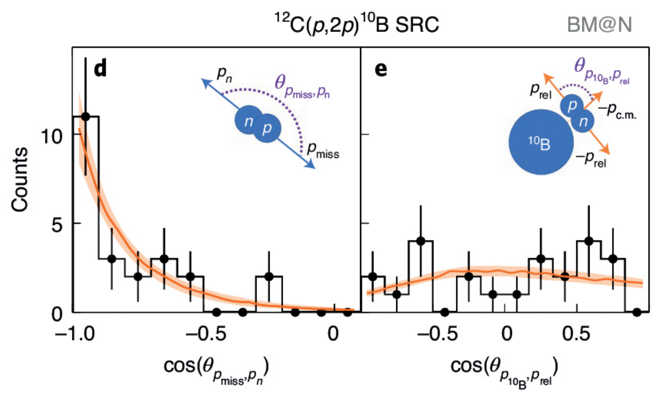

Figure 50. Reconstructed angular correlations between the two correlated nucleons in their CM system (left) and the pair motion with the relative momentum within the pair (right). The insets show the corresponding momenta and the reconstructed angles between them. Figure reprinted from M. Patsyuk et al., Nature Physics 17, 693 (2021) with permission.

R^3B FAIR Phase-0 program

R^3B scheduled three experiments in the FAIR Phase-0 beam time in 2021 using different configurations of R^3B. The first configuration was optimised for the measurement of fission. For part of the program, a liquid hydrogen traget together with a proton tracker was inserted into CALIFA, which will allow for the first time to determine the excitation energy prior to fission. This will enable a future program to determine fission barriers of exotic nuclei. The second configuration corresponds to the standard R^3B high-resolution mode with a vacuum system behind GLAD. This was used to determine cross sections for reactions with neutron-rich tin isotopes. Aim is to extract the neutron-skin thicknesses for those isotopes to constrain the equation of state for neutron-rich nuclear matter. The third configuration was dedicated for the measurement of the $^{16}O(\alpha,\gamma)^{12}C$ reaction in order to extract the differential cross section for the inverse $^{12}C(\alpha,\gamma)^{16}O$ reaction. Since the cross section is very small in the astrophysical important region of low relative energy, the measurement needed a high-intensity ^{16}O beam, and a dedicated experimental setup. For this measurement, a tracking system based on fibre detectors has been developed and build in collaboration with the GSI Detector Laboratory, which was operated completely in vacuum. This tracking system based on fibre detectors will be also used in a different configuration in the R^3B standard high-resolution mode. Since the first fibre detector behind the GLAD dipole is critical in terms of resolution and thickness, and will be placed in the fringe field of the magnet, a new detector with 200 μm square fibres and Silicon-PM readout is being developed in the GSI detector laboratory. The readout electronics of all detectors will be cooled and placed in vacuum as well directly at the detectors.

Outlook for 2022

For 2022, two experiments are foreseen at R^3B, both using the large-acceptance version of R^3B without the vacuum system behind GLAD. One experiment is dedicated to the first measurement and identification of SRC pairs in a radioactive nucleus. The same method as discussed above for the Dubna experiment will be used, but with significantly better detection for the recoil neutron (proton) from the SRC pair with NeuLAND for the neutrons and a resistive-plate chamber (RPC) for proton detection behind GLAD. The RPC has been build by collaboration partners from Portugal and is presently being prepared for the experiment in 2022 by the groups from Coimbra and Lisbon. The second experiment aims at identifying and study resonances in the continuum close to the 2n and 4n thresholds. The correlations of the decay neutrons will be measured by the NeuLAND detector, which will be further upgraded for the 2022 by one more double-plane to further increase the detection efficiency and multi-neutron detection capability. Both experiments use the (p,2p) reaction and the liquid-hydrogen target. In order to precisely measure the scattered protons to allow for missing mass and momentum resolution with large acceptance, a new tracking system based on the FOOT Si-microstrip detectors [R. Spighi et al., FOOT collaboration, Il Nuovo Cimento 42 C, 134 (2019)] is being prepared. The system will cover a larger acceptance and will be significantly faster in readout compared to the previously used AMS system.

Selected publications of 2021

- [1] Patsyuk, M. ; Kahlbow, J. ; Laskaris, G. ; et al.: Unperturbed inverse kinematics nucleon knockout measurements with a carbon beam. Nature physics 17(6), 693 - 699 (2021), DOI:10.1038/s41567-021-01193-4
- [2] Tanaka, J. ; Yang, Z. ; Typel, S. ; et al.: Formation of a clusters in dilute neutron-rich matter. Science / Science now 371(6526), 260 - 264 (2021), DOI:10.1126/science.abe4688
- [3] Aumann, T. ; Barbieri, C. ; Bazin, D. ; et al.: Quenching of single-particle strength from direct reactions with stable and rare-isotope beams. Progress in particle and nuclear physics 118, 103847 (2021), DOI:10.1016/j.ppnp.2021.103847
- [4] Browne, F. ; Chen, S. ; Doornenbal, P. ; et al.: Pairing Forces Govern Population of Doubly Magic Ca54 from Direct Reactions. Physical review letters 126(25), 252501 (2021), DOI:10.1103/PhysRevLett.126.252501
- [5] Boretzky, K. ; Gašparic, I. ; Heil, M. ; et al.: NeuLAND: The high-resolution neutron time-of-flight spectrometer for R3B at FAIR. Nuclear instruments & methods in physics research / A 1014, 165701 (2021), DOI:10.1016/j.nima.2021.165701

4.3 Nuclear spectroscopy

Head: Dr. Jürgen Gerl (GSI)
Authors: Helena Albers, Jürgen Gerl, Magda Górska, Kathrin Wimmer

The Nuclear Spectroscopy Department aims to study the structure of atomic nuclei by performing decay and in-flight gamma spectroscopy experiments at GSI/FAIR and other accelerator facilities all over the world. 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. A recent overview of past, present and future research by the department is provided in [Gerl, J.; Górska, M.; Wollersheim, H. J.; Towards detailed knowledge of atomic nuclei - The past, present and future of nuclear structure investigations at GSI. Phys. Scr. 91 103001 (2016) DOI:10.1088/0031-8949/91/10/103001]. The department is continuously developing necessary detectors and instrumentation for these spectroscopic investigations as well as the associated experimental methodology. 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 collaborations HISPEC/DESPEC, AGATA, MINIBALL, PARIS, PANDA and others. The department maintains a special HISPEC/DESPEC group coordinating the activities of the collaboration and developing and building the related infrastructure for the experimental campaigns at GSI and FAIR.

Highlights in 2021

Nuclear structure experiments

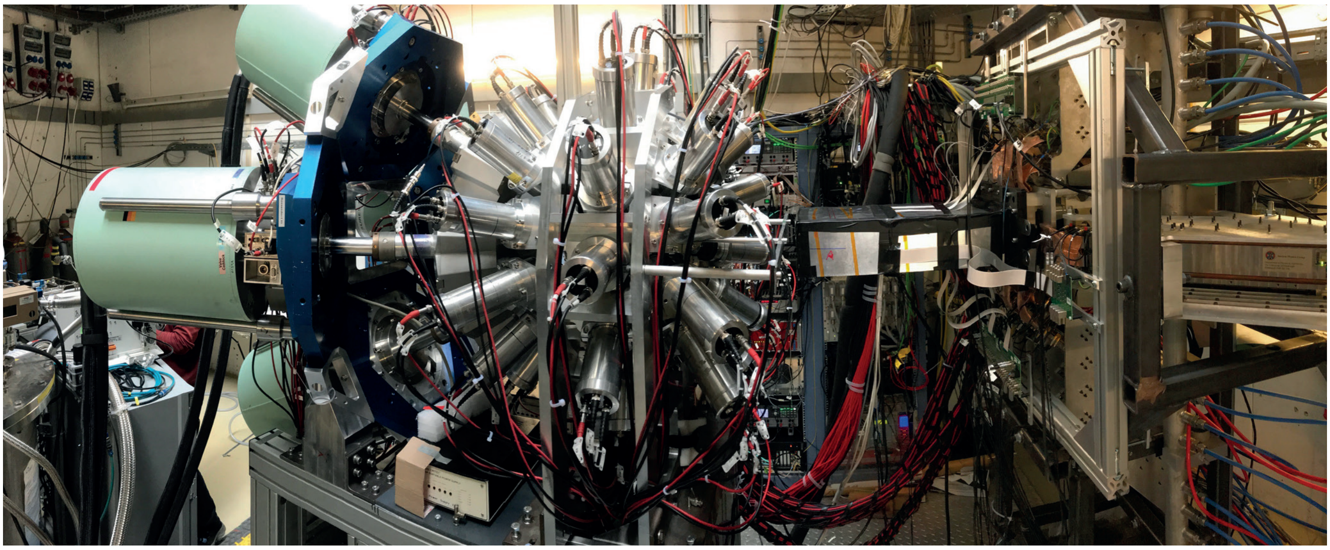

Figure 51. Fast-Timing set-up with AIDA in its wide configuration used at FRS/S4.

Activities concentrated on in-beam commissioning and performance of FATIMA DESPEC [1] experiments within the NUSTAR FAIR Phase-0 campaign. The implementation of the so-called Fast Timing Setup was composed of the AIDA active implanter coupled to the b-Plast timing detector, the FAst-TIMing gAmma-array FATIMA, and the high-resolution gamma-array DEGAS/GALILEO. These detector systems and the FRS set-up were coupled by White Rabbit timing into a common data stream. Despite the Corona pandemic three nuclear spectroscopy experiments were performed:

S452 - The Prolate-Oblate Shape Transition around A~190. In this experiment, beta- and isomer-delayed fast-timing measurements lead to a better understanding of the shape evolution in the Hf-W-Os region toward magic number N=128. This region is characterized by a transition from prolate to oblate nuclear shapes. The found isomerism and the underlying structure is relevant for nuclear synthesis and the astrophysical r-process.

S460 - Investigation of the A~225 island of octupole deformation This experiment investigates the octupole degree of freedom and quadrupole-octupole correlations at the far end of the IOD. New beta-decay information beyond N=126 will test nuclear models for the r-process. The expected shape isomers in ^{220,222}Po will prove the existence of super-deformed bands at low excitation energies. Finally, for the first time alpha-decay channels in the populated fragment region were used for isotope identification.

S496 - Core-breaking in the most neutron-deficient Tin isotopes. For the first time, lifetime measurements in Sn isotopes lighter than 105Sn have been performed (only rel. Coulex for ^{104}Sn). In ^{103}Sn the measurement of B(M1 : $7/2^+$ ->$5/2^+$) will be essential to shed light on the core-breaking contribution of the (7/2+) and (5/2+) states towards ^{101}Sn. In ^{102}Sn the B(E2 : 4^+ -> 2^+) value can probe the nature of first 4^+ and 2^+ states through the interplay of pairing and quadrupole interactions.

The analysis of the data from these experiments as well as the one's performed in 2020 is ongoing. However, important results from earlier internal and external experiments are published [2-4].

Detectors and infrastructure

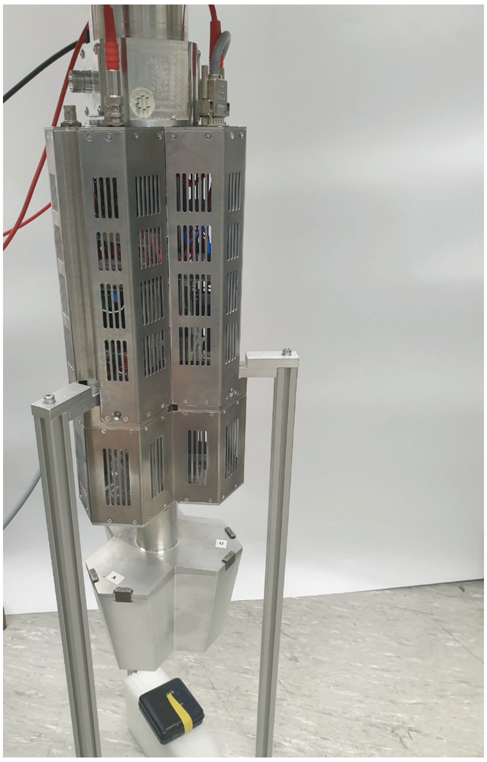

Figure 52. DEGAS first-of-series detector.

In 2020, the work on DEGAS has continued with the successful test of the first-of-series DEGAS detector. Production of the full array consisting of 28 Triple Ge-detectors has started. Due to problems with the supply of electrical coolers, the detectors will be cooled with mini-dewars. This became possible because of the ultra-low cooling power required by the special cryostat developed in house.

Another activity deals with employing a planar Ge DSSD as active implanter for heavy fragments. The idea is to be sensitive to subsequent radioactive decays involving low-energy gamma-rays or conversion electrons. Characterization of the detector at the GSI gamma scanner revealed important results on cross-talk of the strips and their possible correction [5].

In order to simplify the FATIMA electronics, Twinpeaks have widened the GSI TAMEX system, a module that provides linearized energy information based on time-over-threshold. This new module has identical energy resolution and bandwidth as standard QDCs at a fraction of cost. Another initiative has been started to replace the passive FATIMA detector shields by active shields.

For off-beam studies of octupole transitions in ^{228}Th, an active ^{228}Ac source has been developed. It consists of a plastic scintillator used as container for the source material. The beta decay of the source generates a trigger from the scintillation light detected by either a SiPM of a small PMT.

In response to the coronavirus pandemic remote and distance working infrastructure has been further advanced. Monitoring and control of detector hardware, data acquisition and data management/analysis from outside of the GSI campus allowed limiting the number of people on campus to a core minimum.

Applications

Within the ECSIDE - European Consortium for Smart and Innovative Detector Ensemble – project, which aims to develop a novel type of gamma-detection system, R&D on additive manufacturing (3D printing) has started. Printing arrays of inorganic scintillators will be a change of paradigm in detector manufacturing. Only very few attempts are reported in literature concerning ceramics and organic scintillators, while inorganic crystal materials, which provide superior characteristics, were not tackled before. European research so far seems underrepresented in these attempts. Here GSI will enter new routes, e.g. by introducing proprietary methods based on micro crystallites embedded in a suitable substrate. Together with reflectors, holding structures and electrical connections virtually gapless arrangements with minimal dead material budget will be achieved.

Outlook for 2022

In 2022 the department will concentrate on decay studies employing the DESPEC DEGAS High-Resolution spectroscopy Setup and the DTAS full absorption spectroscopy Set-Up at the FRS within the FAIR/NUSTAR Phase-0 campaign. AIDA/bPlast will be used both, in its single and wide version offering 8×8 respectively 24×8 cm^2 implantation area. These experiments will be complemented by experiments at other international facilities. The development of diamond detectors for the LISA project will be started and the development of the full FIMP detector will be continued. In addition, further attempts to print scintillator detectors in the frame of the ECSIDE project are planned. To make best use of the novel detectors, work on AI and ML concepts will be enforced.

Selected publications of 2021

- [1] Li, G. S. ; Lozeva, R. ; Kojouharov, I. ; et al.: Characteristics of the DEGAS-FATIMA Hybrid setup for the DESPEC program at NUSTAR. Nuclear instruments & methods in physics research / A 987, 164806 (2021), DOI:10.1016/j.nima.2020.164806
- [2] Grawe, H. ; Straub, K. ; Faestermann, T. ; et al.: The (6^+) isomer in ^{102}Sn revisited: Neutron and proton effective charges close to the double shell closure. Physics letters / B 820, 136591 (2021), DOI:10.1016/j.physletb.2021.136591
- [3] Valiente-Dobón, J. J. ; Gottardo, A. ; Benzoni, G. ; et al.: Manifestation of the Berry phase in the atomic nucleus ^{213}Pb. Physics letters / B 816, 136183 (2021), DOI:10.1016/j.physletb.2021.136183
- [4] Wimmer, K. ; Korten, W. ; Doornenbal, P. ; et al.: Shape Changes in the Mirror Nuclei ^{70}Kr and ^{70}Se. Physical review letters 126(7), 072501 (2021), DOI:10.1103/PhysRevLett.126.072501 [5] Sharma, A. ; Palit, R. ; Kojouharov, I. ; et al.: Scanning of a Double-Sided Germanium Strip Detector. Advancements in Nuclear Instrumentation Measurement Methods and their Applications. The European physical journal / Web of Conferences 253, 11009, (2021), DOI:10.1051/epjconf/202125311009

4.4 Superheavy elements at GSI and HI Mainz

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* The results presented here are from work carried out before 24. February 2022.

In 2021, activities at GSI focused on the UNILAC beamtime within the FAIR Phase-0 program. These comprised chemistry studies of Nh, high-precision mass measurements of Rf-Db, on-line commissioning of the novel ANSWERS setup, and laser spectroscopy of Fm isotopes. In addition, the analysis of data obtained in previous beamtimes was continued. At HIM, the advancement of technical and methodological developments was most central, for example for applications in laser spectroscopy and mass spectrometry as well as radionuclide layer production for various applications. In addition, preparations for the beamtime 2022 have been performed.

Highlights in 2021

Synthesis

To further our understanding of nuclear reactions, especially on the dynamics of nuclear fusion reactions and effects on the de-excitation of compound nuclei, collaborative experimental work of the SHE-Chemistry department has been carried out at Australian National University's (ANU) Heavy Ion Accelerator Facility, Canberra, Australia [K. Banerjee et al., Phys. Lett. B 820 136601 (2021)] and at the Physics Department of Central University of Kerala, Kasaragod, India [A.C. Visakh et al., Phys. Rev. C 104, 054602 (2021)]. In fall of 2021, a one-week experiment on the study of multi-nucleon transfer reactions has been carried out at the MARA mass separator of University of Jyväskylä, Finland under the lead of the SHE-Chemistry Department (Spokesperson: J. Khuyagbaatar). The data analysis is ongoing.

Nuclear structure

At TASCA, nuclear structure experiments with the nominal large area focal plane detector are ongoing. By employing the sampling ADC "FEBEX" modules developed by the GSI's Experiment Electronics department, multi-isomeric states in ^{256}Rf have been successfully studied [J. Khuyagbaatar et al., Phys. Rev. C 103, 064303 (2021)]. Two isomeric states with half-lives of ≈14 and ≈10 μs have been observed with population rates of ≈18 and >10%, respectively. Such rates are typical for two-quasiparticle high-K isomeric states in this region of nuclei. Therefore, the observed two isomeric states have been attributed to have two-quasiparticle origin. Studying heavy nuclei for the presence of high-K isomeric states, especially those that have longer fission half-lives than their ground states (e.g., ^{250}No), demands to be continued.

Meanwhile, the ground state fission half-lives of neutron-deficient No and Rf isotopes are very short, coming very close to the present experimental limit of about one ms. Analysis of experimental data on the spontaneous fission half-lives of Rf isotopes in relation with their nuclear ground-state configuration hint at a potentially abrupt decrease in half-lives of unknown neutron-deficient Rf isotopes with neutron numbers <149. This suggests that no further neutron-deficient Rf isotopes exist. However, this conjecture was directly related to uncertainties in experimental data on ^{253}Rf. We revisited the decay of ^{253}Rf and identified two fission activities, which are attributed to decays of the two different states with half-lives of ≈12.8 ms and ≈44 μs [1]. In addition, the hitherto unknown α decay in ^{253}Rf, which is followed by α decay of the new isotope ^{249}No with a half-life of ≈15 ms, was observed. Based on our new data, no abrupt decrease in the half-lives of the neutron-deficient No and Rf isotopes is expected, in line with theoretical predictions. It is worth noting that the discovery of ^{249}No was also reported based on independent experiments performed at the SHELS separator at FLNR Dubna [A.I. Svirikhin et al., Phys. Part. Nucl. Lett. 18, 445 (2021)].

Presently, conclusive experimental data on the basic properties of superheavy nuclei are still scarce and are generally limited to data derived from α decay (energy, half-life) and spontaneous fission (half-life). This limitation is not only due to low production rates, but also because of limited detection efficiencies and signal isolation capabilities of the presently available experimental techniques, which do not allow extracting all information on the decay of superheavy nuclei. To solve this problem, the new Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal (ANSWERS) setup was developed in the SHE Chemistry department. In 2021, in-beam commissioning of ANSWERS has been performed in the course of a one-week main beam (spokesperson: J. Khuyagbaatar), in which decays of Rf isotopes were investigated. As preliminary results of this beam time, we observed many multi-coincidence events between α particle, conversion electron(s) and photons associated with decay of ^{257}Rf. The observed data represent a completely new type of experimental data set, which was inaccessible with more traditional previously used setups. This required developing a new method of data analysis, and the data are currently under final analysis. At the same time, ANSWERS showed great potential for studies of fission of the heaviest nuclei, which is a long-term demanding topic that has not yet been satisfactorily explored.

In 2019 and 2020, flerovium isotopes were produced in two runs within FAIR Phase-0, using the fusion-evaporation reactions ^{48}Ca+^{242,244}Pu. They were studied with an upgraded TASISpec decay station positioned at the focal plane of the gas-filled separator TASCA, allowing for detailed nuclear spectroscopy of decay chains starting from ^{286,288}Fl [2] and ^{289}Fl. In 2021, details of the fifteen correlated α-decay chains starting from the odd-A superheavy nucleus ^{289}Fl were investigated. For this isotope, the global data set was roughly doubled. The results from the U310 nuclear spectroscopy experiment call for at least two parallel α-decay sequences starting from at least two different states of ^{289}Fl. Supported by α-electron and α-photon coincidences, α-decay fine structure could be established along the ^{289}Fl chain, and in particular for the α decay of ^{285}Cn, corroborated by Geant4 simulations. Two chains terminated by fast fission of ^{277}Hs, thereby confirming one earlier event observed at TASCA [Ch.E. Düllmann et al., Phys. Rev. Lett. 104, 252701 (2010)]. The observed fine-structure characteristics can be explained by a decay path through low-spin positive-parity states, based on extensive nuclear structure calculations employing the symmetry-conserving configuration mixing theory [J .L. Egido and A. Jungclaus, Phys. Rev. Lett. 125, 192504 (2020)]. The complexity of these “triaxial beyond mean-field” calculations demands about the same real time on multi-core clusters for each decay step and parity as the combined 3-weeks long experiment. Furthermore, previous, revised, and newly derived fission probabilities of even-even superheavy nuclei were compared with various theoretical predictions. The results on ^{289}Fl confirm the overarching picture of high-precision coincidence-spectroscopy measurements providing valuable anchor points for theoretical predictions on the voyage to the Island of Stability. For the future, a conceptually new decay station is being assembled in Lund, which aims to further enhance the quality and sensitivity of nuclear spectroscopy experiments.

The investigation of the heaviest elements by Penning-trap mass spectrometry with SHIPTRAP has been further extended during a successful beamtime in spring 2021. The emphasis was on the investigation of low-lying isomeric states in heavy nuclei that are so long-lived that their investigation by decay spectroscopy is difficult. The high mass resolving power of SHIPTRAP allowed us to determine the absolute excitation energies of these isomeric states accurately and unambiguously for the first time. A low-lying isomeric state in ^{241}Cf was expected to exist according to systematics in N=143 isotones that would predominantly de-excite via internal conversion with an estimated half-life of about 0.2 ms [J. Khuyagbaatar et al., Phys. Rev. C 102, 044312 (2020)]. We have observed this isomer for the first time even though our measurement time was more than one second. Thus, we conclude that the isomer’s half-life exceeds the Weisskopf estimate by about three orders of magnitude [Table of Isotopes, edited by R. B. Firestone, 8th ed. (Wiley, New York, 1996)]. In the region of the superheavy elements, we have performed accurate measurements of the excitation energy of the 4.9 s-isomeric state in ^{257}Rf (mass resolving power up to 10^7). Also, the ground state masses of ^{257}Rf and ^{258}Db have been directly determined with high precision at count rates down to 1 ion/day. These achievements extend the knowledge on the evolution of the N=152 shell closure towards heavier nuclides based on Penning-trap mass spectrometry as a complementary tool to decay spectroscopy. In a parasitic experiment, the interesting members of the α-decay chains ^{206}Fr - ^{202}At –^{198}Bi and ^{204}Fr – ^{200}At – ^{196}Bi were studied. In each of these nuclides two (low-lying) isomeric states, a 7^+ state and a 10^- state, were known from previous investigations of the hyperfine structure and mean-square charge radii [K. M. Lynch et al. Phys. Rev. C 93, 014319 (2016)]. However, the excitation energy of the lowest isomers was experimentally inaccessible and remained unknown. We have now determined this energy directly and with high precision for the first time, extending the previous studies. The analysis of the 2021 beamtime data is ongoing and systematic uncertainties of the method are determined in offline studies.

Atomic physics

The laser spectroscopic investigation of the heaviest actinide elements advanced further in 2021. In the FAIR Phase-0 beam time, we performed detailed laser spectroscopy of ^{249,254}Fm produced via the decay of ^{253,254}No as they are inaccessible in a direct production scheme. Here, the isotope shift of the 25 11^2 cm^{-1} transition was precisely determined, concluding the measurements started in the beam time in 2020. The data are presently under evaluation. In addition, we were able to improve the spectral resolution in the $^1S_1$-$^1P_0$ transition of ^{252}No that was previously studied [S. Raeder et al., Phys. Rev. Lett. 120, 232503 (2018)]. Technical developments focused on an improved operation cycle for the RADRIS method that relies on a collection and measurement cycle that hampers the investigation of short-lived nuclei. Employing fast high-voltage switches was proven to minimize losses in short cycles, enabling measurements of short-lived nuclides such as ^{251}No with a half-life of $T_{½}$=0.8 s and improving the performance during the search for atomic levels in lawrencium that are planned for 2022. For the lawrencium level search an improved theoretical prediction was obtained [3].

For upcoming experiments on nobelium with an improved spectral resolution in laser spectroscopy a new gas jet setup was further commissioned at the HIM using stable isotopes. A thorough characterization of the nozzle shaping the supersonic gas jet was performed using images of the fluorescence from optically excited dysprosium atoms seeded to the gas jet. With these investigations the setup was optimized to spectral resolutions down to 230 MHz corresponding to a gas jet Mach number of M=6.5. These studies pave the way for a measurement of the K=8$^-$ isomer in ^{254}No in the 2022 beam time at GSI.

Additional off-line measurements at the RISIKO setup at the University of Mainz were performed in collaboration with the group of Prof. Klaus Wendt. These became possible in 2021 using a remaining ^{254}Es sample that was originally delivered from ORNL to Mainz in 2019 for laser spectroscopic investigations. This sample was post-irradiated at the high-flux reactor at ILL, Grenoble, France, to breed an increased amount of ^{255}Es ($T_{½}$=40 d). This isotope $β^-$-decays to ^{255}Fm ($T_{½}$=20 h), which can be separated for laser spectroscopy studies. The irradiated sample was shipped back to Mainz just a few days after irradiation, where a separation of ^{255}Fm from its mother ^{255}Es was performed. Multiple Es and Fm samples were prepared for improved laser spectroscopic measurements. This was a unique chance to have access to both short-lived nuclides. In total four fermium separations were performed. Laser spectroscopy was performed on different optical transitions in ^{255}Fm with sample sizes ranging from $1·10^6$ to $7·10^6$ atoms of ^{255}Fm. Eventually, an improved measurement of the hyperfine structure of ^{255}Es with a better spectral resolution was achieved.

Off-line studies in preparation for a measurement of the hyperfine structure of the second lowest-lying nuclear isomer known to date, ^{235m}U, were carried out at University of Jyväskylä within the Laser Ionization and Spectroscopy of Actinides (LISA) MSCA-ITN. For this, several ^{239}Pu recoil ion sources with a total activity of 2.4 MBq were prepared by molecular plating from DMF solution and were characterized both in Mainz as well as in Jyväskylä. Reference studies will be performed with the even-even neighbour ^{236}U, which shows no hyperfine structure; for this, ^{240}Pu sources (about 940 kBq in total) were prepared. The radionuclides of interest will be studied by collinear laser spectroscopy, a technique that provides a high spectral resolution.

Atomic physics via ion-mobility studies

Another method to study the atomic structure has been recently proposed under the name of Laser Resonance Chromatography (LRC) [M. Laatiaoui et al., Phys. Rev. Lett. 125, 023002 (2020)]. This technique is compatible with superheavy element production and is designed to enable laser spectroscopy on lawrencium (Lr) and beyond. It uses laser excitations to change the ratio of ions in the excited metastable state to those in the ground state by optical resonance pumping. Because ions in different states have different transport properties in dilute gases, when they are injected into a drift tube with a constant electric field, they move at different velocities through the drift tube toward a particle detector, enabling state-specific ion separation and resonance detection.

The LRC setup is meanwhile almost complete, and the commissioning phase has already begun with the verification of the vacuum and the functionality of key components such as the buffer-gas stopping cell, the quadrupole mass filter, and the laser systems. The FPGA-based data acquisition system has been commissioned and tested along with the experiment control system. After this phase, testing of the cryogenic drift tube will initially begin with ion mobility measurements on laser-ablated Cu^+ ions.

On the theoretical side, Dirac-Coulomb Hamiltonian and multi-reference configuration interaction (MRCI) methods have been applied to predict the electronic structure of Rf^+ and Db^+ ions, the next two elements in focus after Lr^+. The results for Rf^+ have already been published [H. Ramanantoanina et al., Phys. Rev. A 104, 022813 (2021)]. The MRCI method has also been used to calculate the ion-neutral interaction potentials for the Lr^+-He and Rf^+-He systems. These potentials are important inputs for predicting the transport properties of these superheavy element cations. The results are very promising and will be published soon.

Chemical studies beyond copernicium: nihonium, flerovium, moscovium and perspectives for livermorium

Chemical studies of the superheavy elements were performed at TASCA and focused on Nh and Mc. They picked up on the successful TASCA beamtime in 2020, in which the $^{48}Ca+^{243}Am$ reaction was used to produce 0.17-s ^{288}Mc, which decays into 1-s ^{284}Nh, which was in the focus of these studies. Somewhat unexpectedly, also first signals associated with ^{288}Mc had been observed in 2020. Based on this and on an analysis of previous studies of Nh at FLNR Dubna, Russia and at TASCA [4], an improved setup with an advanced 64-element miniCOMPACT detector was built. In test experiments, a faster and more efficient extraction of short-lived chemically reactive species into the miniCOMPACT gas chromatography and detection setup was achieved, reaching a transport efficiency of up to 50%. During a four-week long beamtime in 2021, the reaction $^{48}Ca+^{243}Am$ was used again to produce ^{288}Mc in the 3n exit channel. The nuclear reaction products were separated in TASCA and thermalized in a modular Recoil Transfer Chamber (RTC) and transferred into the new miniCOMPACT. Eleven decay chains from ^{288}Mc and ^{284}Nh were registered, adding to the seven decay chains observed in 2020. The complete data set is currently under final evaluation and will provide first information on the interaction strength of Nh and Mc towards SiO_2. The preliminary analysis shows excellent agreement with theoretical predictions [5].

On the way to even more short-lived and chemically reactive elements like Lv and Ts, the extraction time to a detection setup has to be reduced further to the order of a few milliseconds, and reference data from the lighter homologs has to be obtained. A reduction of the transport time can be achieved by using of a buffer gas stopping cell for the thermalization of recoiling ions behind TASCA, in combination with the new miniCOMPACT detector. First test experiments with the existing buffer gas cell from SHIPTRAP showed promising results with short-lived α-decaying Hg, Fr, and At radioisotopes [S. Götz et al., Nucl. Instrum. Meth. B 507, 27 (2021)]. The measured efficiency for transporting chemically reactive Fr radioisotopes into the miniCOMPACT setup confirms the setup to be suitable for the identification of isotopes of volatile as well as non-volatile elements. However, the performance of the existing cell in terms of efficiency and extraction time is insufficient for experiments with superheavy elements beyond Mc due to a low stopping power associated with the limited maximum gas pressure. Based on the published conceptual design of the advanced buffer gas cell "UniCell", first prototypes of the ceramic plates for the UniCell funnel were manufactured at the Institute of Electron Technology in Cracow, Poland. Computer simulations and optimizations using the SIMION package were started, as well as the mechanical design of the buffer gas cell chamber.

To obtain a comprehensive data set on the interaction of the lighter homologs with various surface materials, a new isothermal-chromatography setup has been designed, which will allow interaction studies with various surfaces like quartz, gold, or Teflon in a wide temperature range. This is foreseen for the beamtime 2022.

Chemical theory supporting experimental work

With the aim to interpret results of the experimental work on the reactivity of Fl obtained in previous beamtimes at TASCA, energies, Eads, and other adsorption properties of atoms and oxides of Cn and Fl, as well as of the homologous species of Hg and Pb, on the Au(111) and on fully hydroxylated quartz surfaces were calculated on the basis of 2c-DFT BAND calculations and a periodic slab model. The present results with an improved (dispersion corrected) exchange-correlation functional confirm the earlier predicted sequence in the adsorption of the elemental atoms on the gold surface: Pb >> Hg > Fl > Cn. Oxides of Hg, Cn and Fl should be much more reactive with the gold surface than the corresponding atoms, with ≈200 kJ/mol higher Eads values, except for PbO, where $E_{ads}(Pb) > E_{ads}(PbO)$. A striking difference in the geometry of the adsorbed MO molecules was found between group-12 and group-14 elements. An analysis of results for adsorption of the M and MO (M = Hg/Cn and Pb/Fl) species on the hydroxylated α-quartz surface shows that Hg, Cn and Fl atoms should not interact with such a surface at room temperature, while Pb should adsorb on it. Oxides of these elements, on the contrary, should strongly adsorb on quartz with E_{ads} of >100 kJ/mol. Thus, for the gas-phase chromatography column with quartz and gold surfaces of the detectors, FlO and CnO should adsorb in the first section on quartz, while Fl and Cn will be transported further and adsorb on the gold surface in the second section, with E_{ads}(Fl) > E_{ads}(Cn). This agrees with experimental results on the elemental species. To study the formation of small molecules of even heavier, expectedly more reactive elements, formation energies and other properties have been calculated via ADF software for compounds such as LvH_2, LvO, TsH, TsOH, OgH and OgOH, etc. and of their lighter homologs. Optimal formation reactions have been suggested.

Quantum chemical method developments

A particular focus of software developments in 2021 was put on enhancing the accuracy and efficiency of (multiconfigurational) relativistic quantum chemical approaches applicable to chemical studies in SHE chemistry. In continuation of our efforts to treat scalar-relativistic effects, spin-orbit coupling and electron correlation effects on an equal footing, we put forward a simplified, yet accurate state-interaction ansatz within the framework of the density matrix renormalization group approach (DMRG) [L. Freitag et al., J. Chem. Theory Comput., 17, 7477 (2021)]. The latter enables faster and more affordable large-scale multiconfigurational calculations with the inclusion of spin-orbit coupling and also makes DMRG-based ab initio excited-state molecular dynamic simulations accessible for future applications. Moreover, to alleviate the computational cost associated with genuine relativistic four-component quantum chemical calculations, we formulated and implemented a new ansatz for two-electron scalar- and spin-orbit picture-change corrections applicable to exact two-component Hamiltonians for relativistic quantum chemistry. First studies on (molecular) compounds of the superheavy elements Cn, Lv and Og showed that the resulting new two-component Hamiltonian models yield molecular properties that are within spectroscopic accuracy (< 1 meV) of the parent four-component data when probing the core (Mössbauer and X-ray ionization spectroscopy) as well as the valence electronic structure (reaction energies and valence excited states).

Actinide target production developments

Superheavy element production relies on optimized long-term stable targets of rare actinide isotopes. Improved methods are needed to produce targets in a thickness range up to >1 mg/cm^2, able to withstand highest beam intensities as provided by ever more powerful accelerators. To this end, a two-prong approach is currently pursued. On the one hand, fundamentals of the most frequently used production technique, molecular plating (MP) are studied and modern electrochemical production processes are evaluated in cooperation with the DECHEMA Research Institute, Frankfurt. On the other hand, microscopic and spectroscopic studies of heavy-ion beam-induced changes in f-element layers are performed together with the Materials Research Department.

Molecular-plated lanthanide targets, both unirradiated ones as well as targets that were previously irradiated with different fluences of 8.6-MeV/u ^{197}Au at the GSI Materials Research department's M-Branch, were analysed with various techniques. Ion-beam analysis performed at the Ion Beam Center at Helmholtz-Zentrum Dresden Rossendorf (HZDR) showed a decrease of the carbon and oxygen content with increasing beam dose. To identify elemental and structural modifications, additional analytical methods, such as infrared spectroscopy (IR), Raman spectroscopy (Raman), X-ray photoelectron spectroscopy (XPS) and grazing incidence diffractometry (GIXD) were applied at the JRC-Karlsruhe in the frame of the RI Open Access scheme ActUsLab; these data are currently under final evaluation. In 2021, a new set of lanthanide targets was irradiated with 5.9-MeV/u ^{48}Ca ions at the TASCA beamline. Some of the samples were produced by the classical MP technique, and others by a novel electrochemical production pathway based on triflate precursors. To facilitate analysis in laboratories not rated for handling radioactive materials, the targets are currently stored to allow decay of beam-induced radionuclides; they will be analysed in 2022.

A multitude of further targets and sources, mostly of actinides, was prepared in the SHE Chemistry section at HIM for studies within our groups, e.g., at TRIGA-TRAP and SHIPTRAP, as well as for use in collaborative work, including Am, Cm, and Cf samples provided for laser spectroscopy studies at the RISIKO laser mass separator. The study of various aspects connected to the exotic low-energy ^{229m}Th isomer is performed in different collaborating groups. For such work, two ^{233}U recoil sources providing the α-decay daughter $^{229(m)}$Th prepared by MP were shipped to KU Leuven, where $^{229(m)}Th^+$ will be extracted by a gas-jet to a laser ionization and spectroscopy setup. Metallic ^{232}Th laser ablation targets were shipped to the University of Granada, where Penning-trap based studies will be performed at the TRAPSENSOR facility, first with ^{232}Th and later with ^{229m}Th. A liquid source of ^{228}Ra placed in a container made from scintillating material was provided to the GSI nuclear spectroscopy department for use at the DESPEC setup. For this, 26.5 kBq ^{228}Ra were separated from about 10 g of ^{nat}Th. For fission studies at the LOHENGRIN mass spectrometer at ILL Grenoble, old targets containing 1 mg of ^{239}Pu were reprocessed. From this material, five new targets with activities of 20-1000 kBq were produced via MP and employed in experiments in 2021. The JRC Geel, Belgium, aims on detailed investigations of undisturbed fission products from spontaneous fission sources like ^{248}Cm and ^{252}Cf, necessitating thin sources of spectroscopic quality placed on extremely thin backings like 10 µg/cm² carbon foils or 24 µg/cm² polyimide foils. The Drop-on-Demand (DoD) printing technique was employed. Parameter studies of the wetting behaviour of different solvents were performed to identify a system that provides thinner deposit layers on polyimide films than the standard water/acid-based system. Ethanol/water mixtures were found to provide superior layers as demonstrated with an ^{243}Am source and verified at JRC Geel. Samples of ^{248}Cm and ^{252}Cf will be produced in 2022. Large-area ^{241}Am calibration sources are needed for the online calibration of a special detector array used in studies of neutron decays at the TRIGA Mainz and the ILL Grenoble. Fourteen such sources with about 6-7 kBq of ^{241}Am each and four with about 25 kBq each were produced by DoD printing on Ti substrates.

Selected publications of 2021

- [1] Khuyagbaatar, J. ; Brand, H. ; Cantemir, R. A. ; et al.: Spontaneous fission instability of the neutron-deficient No and Rf isotopes: The new isotope 249No. Physical review / C 104(3), L031303 (2021), DOI:10.1103/PhysRevC.104.L031303
- [2] Såmark-Roth, A. ; Cox, D. M. ; Rudolph, D. ; et al.: Spectroscopy along Flerovium Decay Chains: Discovery of ^{280}Ds and an Excited State in ^{282}Cn. Physical review letters 126(3), 032503 (2021), DOI:10.1103/PhysRevLett.126.032503
- [3] Kahl, E. V. ; Raeder, S. ; Eliav, E. ; et al.: Ab initio calculations of the spectrum of lawrencium. Physical review / A 104(5), 052810 (2021), DOI:10.1103/PhysRevA.104.052810
- [4] Yakushev, A. ; Lens, L. ; Düllmann, C. E. ; et al.: First Study on Nihonium (Nh, Element 113) Chemistry at TASCA. Frontiers in Chemistry 9, 753738 (2021), DOI:10.3389/fchem.2021.753738
- [5] Pershina, V. ; Iliaš, M. ; Yakushev, A._ Reactivity of the Superheavy Element 115, Mc, and Its Lighter Homologue, Bi, with Respect to Gold and Hydroxylated Quartz Surfaces from Periodic Relativistic DFT Calculations: A Comparison with Element 113, Nh. Inorganic chemistry 60(13), 9796 - 9804 (2021), DOI:10.1021/acs.inorgchem.1c01076

5. Research of the PANDA Departments

Coordination: Prof. Dr. Klaus Peters (JWGU Frankfurt, GSI)
Author: Klaus Peters

The PANDA experiment belongs to a new generation of hadron physics experiments, hereby building on the experiences and successes of previous generations. It features a modern multipurpose detector. The combination of a high-quality antiproton beam at the High Energy Storage Ring (HESR), an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. GSI is the PANDA lead-lab which coordinates the international efforts of the whole PANDA collaboration (65 Institutes in 18 Countries) to get the detector ready for a rich physics program. This involves overall and technical coordination and integration, core-software and trigger development as well as the full construction of the German in-kind DIRC for PANDA and several individual R&D and construction work packages connected to the Magnets, the Electromagnetic Calorimeter (EMC), Luminosity Detector (LMD), the Cluster-Jet Target, the experiment infrastructure and the Gas Electron Multiplier (GEM) detector. This is accompanied by Phase-0 activities like cooperation for the GlueX-DIRC at Jefferson Lab (Newport News, USA) and data analysis at GlueX and BESIII at IHEP (Beijing, PR 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 and with the PANDA Coordinators at FAIR.

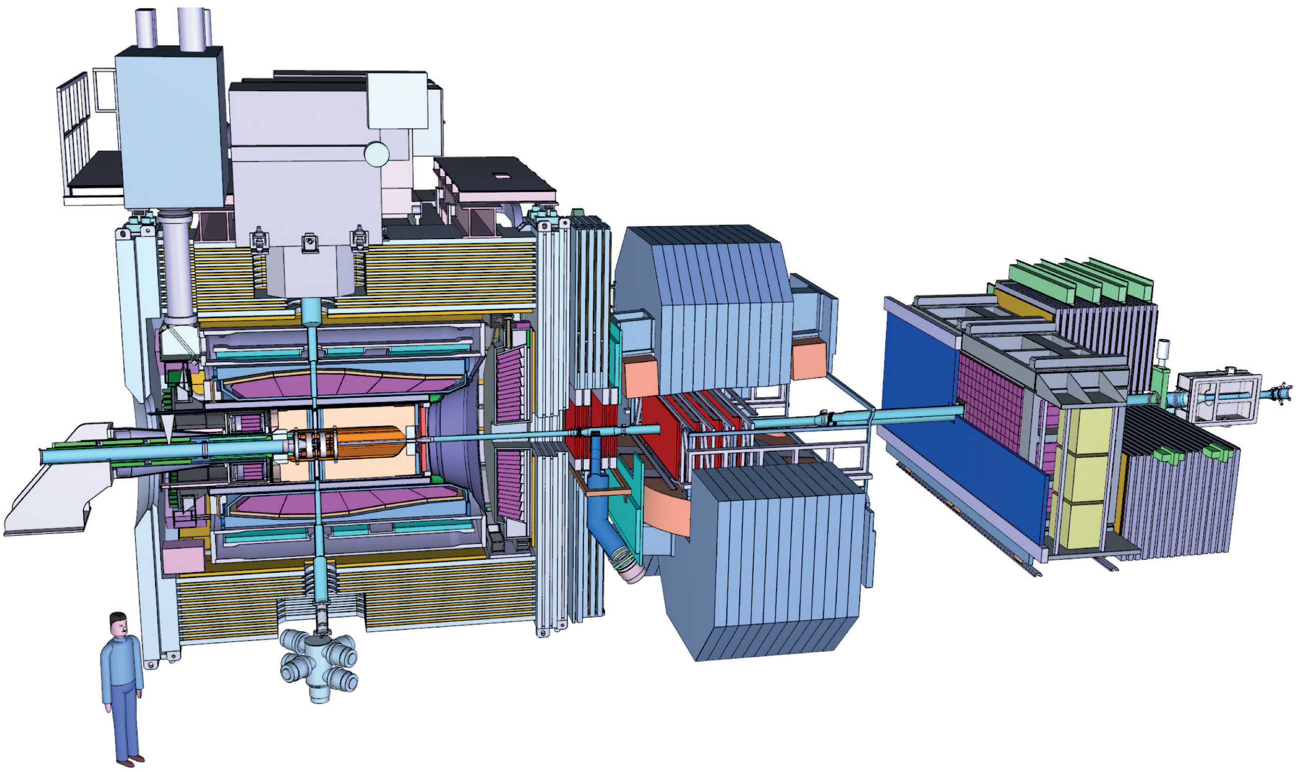

Figure 53. PANDA Detector (Illustration by J. Lühning, GSI).

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 TOF, the forward and backward endcaps of the EMC, 12 slices (out of 16) of the Barrel EMC, 2 stations (out of 3) of the GEM detector and 4 (out of 6) stations of the forward tracker, the Forward TOF, the Forward calorimeter and the Luminosity Detector. There is a variety of tasks ongoing in the Hadron Spectroscopy Department for the construction and assembly of the detector as well as its operation and analysis. Progress in magnet assembly, infrastructure and routing, and central mechanical support elements as well as scrutiny of final designs and the follow-up on detector production elsewhere have been accomplished by the PANDA technical coordination team while the software group was focussing on the analysis of FAIR Phase-0 experiments.

The focus of the PANDA Detectors department in 2021 was on the series production of the components for the PANDA Barrel DIRC. A new setup was commissioned in the optical lab at Old Dominion University (ODU), USA in a cooperation between ODU, Catholic University, USA and GSI to characterize the focusing properties of several prototypes of the innovative spherical focusing lens and to finalize the design in time for the call for tenders, planned for 2022. Measurements of the optical quality of the fused silica bars, produced in 2020/2021 continued in the DIRC lab at GSI. Following the start of the series production of the micro-channel plate PMTs, quality assurance test procedures were developed at Erlangen University to prepare for the first delivery in early 2022. In the context of FAIR Phase-0, the development of new calibration and reconstruction methods for the GlueX experiment resulted in a significant improvement in the understanding of the particle identification performance of the GlueX DIRC detector.

5.1 Hadron spectroscopy

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

Highlights in 2021

PANDA solenoid magnet

Production of components of the PANDA Solenoid magnet progressed well. The manufacturing of the cryostat and cold mass has started. First samples of Super-Conducting (SC) strands were tested and are well within specs. A procedure for thermal curing of pure aluminum was tested giving an Residual Resistance Ratio (RRR) value above 1000. Together with the results from the strands a very stable SC cable can be expected for the PANDA solenoid. A first of series of the cable is expected in spring 2022. In addition, the ATLAS magnet group from CERN supplied short conductor pieces for the bus bars of the PANDA solenoid.

HESR-PANDA chicane spectrometer dipole

A contract for construction of the HESR PANDA Chicane dipole magnet was concluded with BINP following the completion of the design work for this magnet at BINP. A plan review of the construction contract was conducted, and a conceptual design was drafted for the power converter of the magnet. Material procurement started with the order of steel and the copper material for the coils. Tooling design for coil winding production has also started recently.

Review and approval of reports

For the PANDA EMC Technical Design Report (TDR) from 2008 a report on updates and design progress was submitted to FAIR in 2020 which was reviewed and approved in 2021 stating commendations on the excellent progress and production development details. The TDR of the Data Acquisition and Event Filtering system was submitted to FAIR in 2020 and reviewed and approved in 2021. The review committee with external DAQ experts from CERN experiments commended the flexible staged setup and the precision timing system.

In addition, we received the approval of the Infrastructure and Installation Technical Report that describes the technical layout and the cost assessment for the infrastructure of the PANDA experiment, comprising all common supports and the supply infrastructure in the framework of integration requirements and installation procedures. The cost figures are an important input for the PANDA Construction Memorandum of Understanding which will be signed in 2022.

GEM tracker TDR and tests

The TDR draft of the PANDA GEM Tracker was submitted to the collaboration for internal review. Following the recommendations of the reviewers, additional simulations of hit occupancy were done. A Scalable Readout System (SRS) based on the ATLAS VMM3a chip hybrid was set up at the CERN GDD detector-lab with the support of colleagues of the RD51 collaboration. Participation at the RD51 beam time at CERN SPS gave the PANDA GEM team the opportunity to prepare for similar tests with the PANDA GEM2D Demonstrator to come in 2022. The results will enter the GEM TDR after analysis of first data.

PANDA hall and infrastructure

Following the Infrastructure and Installation Report, detailed work on planning of supports, cooling and supply systems continued in 2021. The planning of the cryogenic infrastructure is shown in Figure 54. A liquid nitrogen (LN_2) heat exchanger and evaporator will serve to cool gaseous helium for the solenoid shield and provide gaseous N_2 for flushing detectors. They will be placed on a common foundation with the large outside gas tanks.

DOI:10.15120/GSI-2022-00454

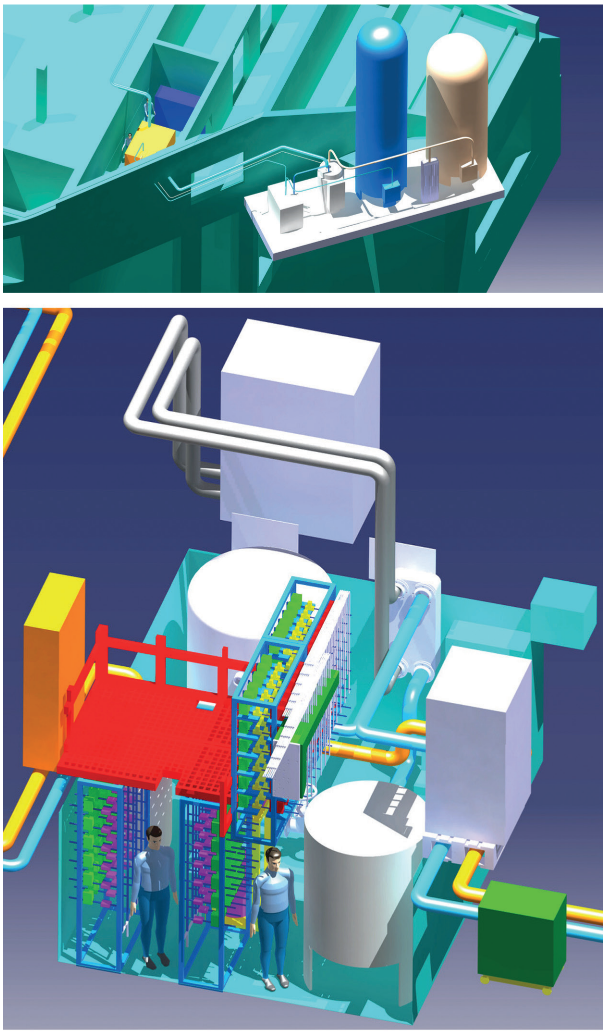

Figure 54. LN2 plant on common foundation with gas tanks. Bottom: Pumping pit with 3 under-pressure systems (Both illustrations by D. Glaab, GSI).

Further infrastructure planning regards the under-pressure rack cooling (see bottom part of Figure 54). The distribution circuits are planned and sizes of tubes and the common reservoir are calculated. The size of the pump pit below the hall floor previously foreseen only for the MVD and EMC under-pressure cooling systems was adjusted to house all three systems.

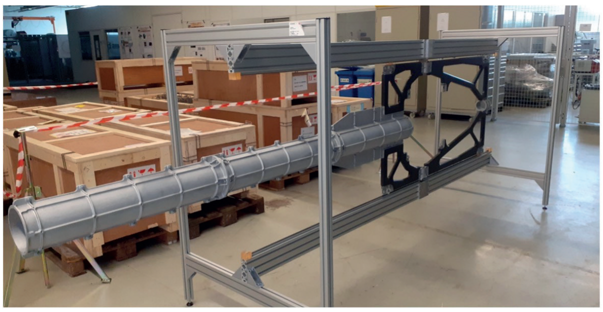

Figure 55. Assembled Central Space Frame (CSF) prototype (Photo by S. Koch, GSI).

Further design work was done for the Central Space Frame (CSF) which will support the beam-target pipe, the MVD with services and the STT. The CSF rail will be embedded within the Barrel DIRC structure. The main parts of the CSF will be made of a hollow carbon fiber composite profile with aluminum inserts to clamp the parts and interface to the supported systems. To test stability and mounting procedures a prototype (see Figure 55) was assembled with extensive tests planned for 2022.

Software trigger

For the PANDA Software Trigger the investigations concerning the application of Machine Learning (ML) techniques have progressed significantly. The results have been presented in an international context, and a dedicated publication is in preparation. In summary, with binary classification convolutional neural networks, the signal efficiency was increased by up to 140% compared to the conventional selection approach, while keeping the background at the required level of 1/1000.

The inconsistent findings by LHCb concerning the nature of the $\chi_{c1}(3872)$, being either a compact tetraquark, a molecular D^0 anti-D^{0*} state or something completely different, substantiate, that the precise measurement of the line shape by PANDA remains the most expedient technique to eventually distinguish different models. As an addition to the results published 2019 about the expected precision of a Breit-Wigner width or a Flatté model parameter measurement, an investigation has been carried out to determine the discrimination power for these two models achievable by a PANDA cross-section scan. The repeated simulation of many of these scans under different assumptions of the true nature of $\chi_{c1}(3872)$ revealed, that even in the starting phase of the experiment, PANDA will offer at least a ten times higher probability to correctly identify the nature of the state compared to the most sensitive measurement so far published by LHCb in 2020. This analysis has been presented in international workshops and conferences.

BESIII analysis

The focus of BESIII data analysis is directed to the search for yet unknown decay channels of the puzzling and presumably exotic ψ(4230)/ψ(4330) resonances. In that respect a search for inclusive hyperon production in reactions $e^+e^- \rightarrow \Lambda X$ is still being carried out. Goal of the investigation is the energy dependent cross section, which has already been extracted in a preliminary way. At a first glance there are hints for the presence of one or more resonances in the cross-section spectrum.

GlueX analysis

The measurement of the production cross section of φ(2170) in photon scattering reactions $\gamma p \rightarrow \varphi \pi^+ \pi^- p$ based on data of the GlueX experiment taken from 2016 – 2018 is still in progress. This state is believed to be a possible strangeonium partner state of the above mentioned ψ(4230). To improve the sensitivity of the method as well as the accuracy of the result, the fit model has been extended to a coherent setup, being able to describe possible interference effects between the signal and competing reactions.

DAC21

In November PANDA took part in a Data Challenge (DAC21) together with other FAIR experiments (CBM, R3B) for the ESCAPE Data Lake distributed storage. The goal was to establish the feasibility of and connectivity to the Data Lake by the exchange of simulation data. In total 25 million events (~5 TB) of PANDA background simulation have been created, half as fallback data and the other half in live mode. The results and performance have been reported to the DAC21 organizers.

Outlook for 2022

- Award of first infrastructure contract (intended for BINP).
- Manufacturing of components of PANDA magnets (both Solenoid and Dipole).
- Submission of GEM TDR to FAIR.
- Finalize GlueX cross section measurement.
- Investigations for unsupervised event tagging with BES data.

Selected publications of 2021

- [1] Barucca, G. ; Davì, F. ; Lancioni, G. ; et al.: Study of excited Ξ baryons with the PANDA detector. The European physical journal / A 57(4), 149 (2021), DOI:10.1140/epja/s10050-021-00444-5
- [2] Barucca, G. ; Davì, F. ; Lancioni, G. ; et al.: PANDA Phase One. The European physical journal / A 57(6), 184 (2021), DOI:10.1140/epja/s10050-021-00475-y
- [3] Nerling, F.: Charm (-onium) physics at PANDA. Proceedings of 10th International Workshop on Charm Physics — PoS(CHARM2020) - Sissa Medialab Trieste, Italy, 2021 10th International Workshop on Charm Physics, CHARM2020, Mexico City, Mexico (online), 31 May 2021 - 4 Jun 2021 Sissa Medialab (2021), DOI:10.22323/1.385.0004
- [4] Ablikim, M. ; Achasov, M. N. ; Adlarson, P. ; et al.: Study of the process e^+e->φη at center-of-mass energies between 2.00 and 3.08 GeV. Physical review / D 104(3), 032007 (2021), DOI:10.1103/PhysRevD.104.032007

5.2 PANDA detectors

Head: Dr. Jochen Schwiening (GSI)
Author: Jochen Schwiening

The main objective of the department is the development and construction of solid-state Ring Imaging Cherenkov Detectors, known as DIRC (Detection of Internally Reflected Cherenkov Light) counters. These compact and robust 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, GlueX (at Jefferson Lab, USA), and the future Electron-Ion Collider (EIC) detector (at BNL, USA).

Highlights in 2021

Series production and quality assurance of PANDA Barrel DIRC components

GSI is the lead group for the PANDA Barrel DIRC detector, a German in-kind contribution to PANDA. The activities are performed in cooperation with the Universities of Erlangen and Mainz and the HI Mainz and focused in 2021 on the fabrication and quality assurance of the most expensive and longest lead-time PANDA Barrel DIRC components, the fused silica bars, and the micro-channel plate PMTs (MCP-PMTs). Following the successful conclusion of the series production of the DIRC bars in March 2021, the optical quality of the bars is being evaluated in the DIRC lab at GSI using a motion-controlled system with multiple lasers to determine the probability for photons to propagate inside the bar by total internal reflection. Initial measurements confirm that the quality of the bars meets all requirements. The series production of the MCP-PMTs has started and the delivery of the first lot is expected in early 2022. The sensors will be characterized at Erlangen University, including detailed scans of the quantum efficiency, gain, and timing precision, as well as long-term measurements of the sensor lifetime. The setup for these quality assurance measurements was completed and exercised using pre-production prototypes.

Evaluation of the lens design for Barrel DIRC detectors at PANDA and the Electron-Ion Collider

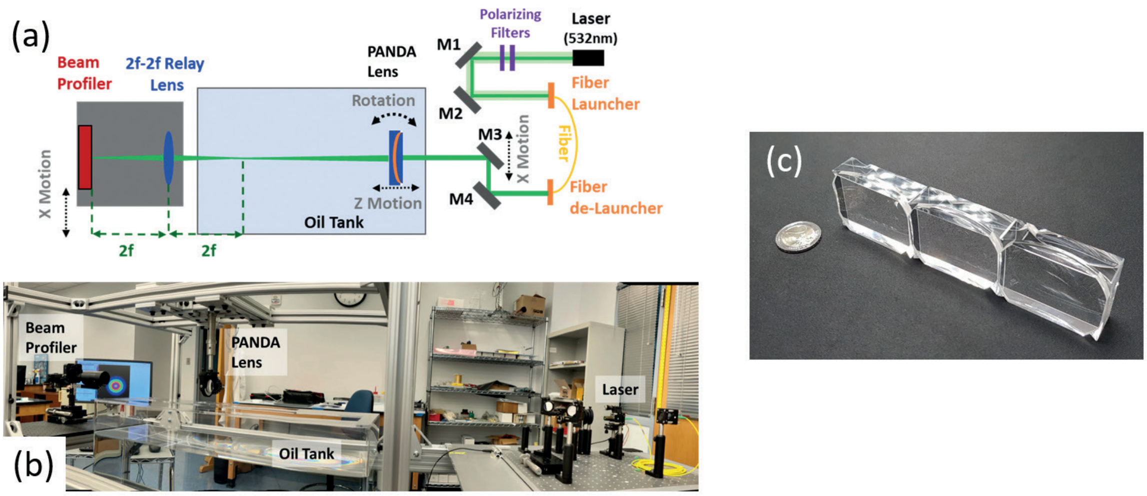

Figure 56. Schematic (a) and photo (b) of the new laser setup at Old Dominion University for the characterization of prototypes of the PANDA Barrel DIRC 3-layer spherical lens prototypes (c). (Illustration (a) and photo (b) by G. Kalicy, CUA; photo (c) by C. Schwarz, GSI).

The innovative 3-layer spherical lens is a key element of the PANDA Barrel DIRC. A layer of a high-refractive index material, such as lanthanum crown glass or sapphire, is embedded between two layers of synthetic fused silica to produce a combination of defocusing and focusing transitions to image the Cherenkov light. This results in a flattened focal plane that matches the location of the photon sensors in the compact detector layout while avoiding the photon losses associated with air gaps present in conventional multi-layer focusing lens systems. Following the successful validation of the lens concept during a joint PANDA/EIC DIRC beam test at CERN in 2018, this lens design was also adopted for the proposed Barrel DIRC counter for the future EIC detector. This synergy resulted in a cooperation between Catholic University (CUA), USA, Old Dominion University (ODU), USA, and GSI with the goal of comparing the focusing properties of different DIRC lens designs. The team, led by Prof. Grzegorz Kalicy (CUA), constructed and commissioned a new setup (shown in Figure 56) in the optical lab at ODU. Lens prototypes, built by industry using different materials for the high-refractive index layer, are placed in a tank filled with mineral oil to match the refractive index of fused silica, and scanned with a laser beam. A CMOS camera beam profiler determines the size of the laser beam spot at different locations behind the lens and the 3D shape of the focal plane is extracted from measurements of the focal length for different impact angles and positions of the laser on the lens. The setup and analysis procedure were commissioned using a commercial achromatic lens and a physical GEANT simulation of the setup was developed. Results for the most recent prototype lens for PANDA are expected in early 2022, in time to finalize the design and start the call for tenders in 2022.

FAIR Phase-0: simulation and reconstruction of the GlueX DIRC detector data

The GlueX experiment was upgraded in 2018/2019 by adding a DIRC detector to improve the PID capability for the high-luminosity GlueX-II program. The GSI group participated in this DIRC upgrade in the context of FAIR Phase-0 by contributing to the design, operation, and data analysis of the GlueX DIRC. The simulation and reconstruction code, initially developed for the PANDA Barrel DIRC, were applied to the GlueX data from 2020 to validate the software with experimental data. New calibration and alignment procedures, as well as a new reconstruction method, were developed, leading to a significant improvement in the agreement between experimental data and simulation.

Outlook for 2022

The series production of PANDA Barrel DIRC components and the corresponding quality assurance will continue in 2022. Calls for tenders for the lenses and the expansion volume prisms are expected to start in the spring of 2022. The mechanical design of the PANDA Barrel DIRC, based on elements made from carbon-fiber-reinforced polymer (CFRP), will be implemented in prototypes to validate the performance and determine the possible impact of the materials on the optical quality of the DIRC bar surfaces. Preparation for the gluing of the fused silica bars and lenses, and the assembly of the DIRC bar boxes, will start in the summer of 2022 at the DIRC lab at the HI Mainz.

Selected publications of 2021

- [1] Ali, A.: Particle identification with the PANDA Barrel DIRC and the GlueX DIRC. Frankfurt : Universitätsbibliothek Johann Christian Senckenberg 124 S. (2021) = Dissertation, Johann Wolfgang Goethe-Universität Frankfurt, 2021
- [2] Schepers, G. ; Belias, A. ; Dzhygadlo, R. ; et al.: PANDA Barrel DIRC: From Design to Component Production, Preprint arXiv:2201.10834
- [3] Abdul Khalek, R.; Accardi, A.; Adam, J.; et al.: Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report, (2021), Preprint arXiv:2103.05419

6. FFN (FAIR Forschung NRW)

Head: Prof. James Ritman (RU-Bochum, GSI)
Authors: Ralf Engels, Waleed Esmail, Dieter Grzonka, Andro Kacharava, Philipp Kampmann, Livia Ludhova, Johan Messchendorp, Jörg Pretz, Jenny Pütz, Susan Schadmand, Tobias Stockmanns, Peter Wintz, Huagen Xu

Highlights in 2021

HADES upgrade as part of the PANDA FAIR Phase-0 program

FFN is contributing two major components to the HADES upgrade: i.e. a strawtube detector (STS) to extend the tracking capabilities and a scintillation detector system (Inner-TOF) for an improved trigger selectivity. The STS1 consists of 704 straw tubes arranged in four double-layers that cover polar angles from 0.5° to 7°. Signal readout is performed by PASTTREC ASICs connected to TRB3 boards. The Inner-TOF detection system consists of trapezoidal shaped scintillator modules covering the six innermost HADES MDCs. Each scintillator module includes three independent plastic scintillator elements with 6.4 mm thickness, and is read out with 12 6x6 mm^2 SiPMs (MicroFC-60035), which provide fast output signals (width ≈ few ns) passed to a PADIWA board connected to a TRB3sc board. The performance of the detector systems was studied with cosmics, ^{90}Sr-source and proton beams from COSY. All straws showed excellent performance with comparable signals and stable operation and the Inner-TOF achieved close to 100% efficiency with signals from all 12 SiPMs in almost every event.

The complete STS and two prototype modules of the Inner-TOF were operated for a test beamtime at HADES. Good performance and stable operation of the STS was verified. The Inner-TOF prototype demonstrated its ability to provide an improved trigger system and the complete Inner-TOF detector is now installed at HADES.

Investigation of the Σ^0 production mechanism at HADES

The Σ^0 hyperon production mechanism was investigated using existing proton-proton data from HADES at a beam kinetic energy of 3.5 GeV. The total production cross section is found to be $\sigma = 18.7 \pm 1.0(stat) \pm 1.7(syst)$ μb. Differential cross section distributions of the exclusive channel pp-> $pK^+\Sigma^0$ were analyzed. A contribution of interfering nucleon resonances is concluded from the helicity angular distributions. The Bonn-Gatchina partial wave analysis framework indicates that the N*(1710) and either the N*(1900) or Δ*(1900) are required by the fit. Due to the limited statistics, an unambiguous determination of the relative contributions was however not possible.

PANDA

One longstanding open point for the PANDA reconstruction software is the finding of tracks from secondary particles. Without including the primary interaction point to the fit, the track finding complexity rises by an order of magnitude, so far preventing an efficient solution. A new algorithm was developed by GSI-FFN, which uses a smart layer concept within the STT detector to select three points of a track, calculates the circle parameters based on the isochrone radii and adds the missing hits to the track. This concept has very high track finding efficiencies of above 85 % for higher momentum hyperon particles with decay lengths of several centimetres.

A feasibility study of the channel $\bar{p}p$-> $\bar{\Xi}^+\Lambda K^-$ has been performed including the two resonances Ξ(1690) and Ξ(1820) in the ΛK^- system [1]. This study demonstrated the ability of PANDA to reconstruct between 3% and 5% of the generated signal events, with sufficient background suppression. Based on these results the possibility to determine the spin and parity quantum numbers of several Ξ resonances has been investigated by employing a partial wave analysis with the PAWIAN software framework. It has been determined that the spin-parity assignment of these resonances is possible with data from a few days of data taking with PANDA.

The spectroscopy of baryons with strange quarks is one of the key pillars of the overall PANDA physics program in the first phases of data taking. This aspect has been highlighted in a review article "PANDA Phase One" released in 2021 [2], which is the first in a series of articles that will eventually be compiled as PANDA's physics book. These activities are led by FFN-GSI and GSI.

KOALA

The KOALA team built a new plastic scintillator detector for the forward coincidence measurement and successfully commissioned the experiment at COSY. The proton beam test validated the experiment principles as well as the detector techniques and confirmed the specifications for the forward acceptance of 0.37°< θ <1.5° needed in the final design of the KOALA operation at HESR. Technical details of the KOALA setup at COSY were published in Nuclear Inst. and Methods in Physics Research A, Vol. 1019, 165849, 2021.

Experiments at Jefferson Lab

After the Scheduled Accelerator Down (SAD) was successfully completed, members of GSI-FFN participated in several experiments during September-December 2021. In Hall D the GlueX detector acquired data on the eta radiative decay width via the Primakoff effect (E12-10-011) and started measurements of short-range correlations with real photons (E12-19-003). In addition, we participated in the Hall B CLAS12 measurements of electron scattering from multiple nuclear targets to study short range correlations in nuclei and to benchmark neutrino event selection, energy reconstruction and event generators (PR12-18-003).

Progress towards JEDI

The JEDI collaboration has successfully conducted a second precursor experiment (Precursor-II) at COSY in 2021 to search for the deuteron EDM using the improved conditions of the polarized beam and related instrumentation.

A further highlight of 2021 was the publication of the report "Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study", as a CERN Yellow Report (CERN-PBC-REPORT-2019-002). Furthermore, the collaboration hosted WE-Heraeus Seminar #744 (Towards srEDM Measurements), and presented their results at meetings such as the CERN PBC (Physics Beyond Colliders) diversity program, the European JENAA (Joint ECFA-NuPECC-APPEC Activity) initiative and the Snowmass process, which is part of the strategic planning of the US Particle-Physics community. These activities have been reported in Nucl. Phys. News, Vol. 31, No. 2, 2021.

As a scientific milestone, the JEDI collaboration published an investigation of coherent betatron oscillations of a deuteron beam at COSY, excited by a detuned RF Wien filter (WF) [3]. The beam oscillations were detected by conventional beam position monitors. It was shown that oscillation amplitudes down to 1 μm can be detected. The interpretation of the response of the stored beam to the detuned RF WF is based on simulations of the beam evolution in the lattice of the ring and realistic time-dependent 3D field maps of the WF. Future measurements of the electric dipole moment of protons will, however, require control of the relative position of counter-propagating beams in the sub-picometer range. Since the stored beam can be considered as a rarefied gas of uncorrelated particles, it has been demonstrated that the amplitudes of the zero-point (ground state) betatron oscillations of individual particles are only a factor of about 10 larger than the Heisenberg uncertainty limit. As a consequence of this, it is concluded that quantum mechanics does not preclude the control of the beam centroids to sub-picometer accuracy. The smallest Lorentz force exerted on a single particle that could be determined is 10 aN.

Neutrinos (Borexino, JUNO)

The neutrino physics group specializes in low-energy neutrino physics with liquid scintillator (LS) based detectors, and is a member of the Borexino and JUNO collaborations.

The Borexino experiment features a 280-ton LS detector with the world's highest radiopurity, and took data from 2007 until 2021. It focuses on the detection of solar neutrinos and geo-neutrinos as well as on the searches for rare processes in coincidence with astrophysical events. Borexino observed solar neutrinos from the pp chain and CNO cycle providing a unique and comprehensive test of the Sun as a nuclear fusion engine. With a substantial contribution from our group, Borexino developed in 2021 a new method, called Correlated and Integrated Directionality (CID), that exploits the directional Cherenkov light in a LS detector, in order to disentangle the solar neutrino signal, correlated with the known Sun's position, from the isotropic background [M. Agostini et al., DOI:10.1103/PhysRevD.105.052002 and DOI:10.1103/PhysRevLett.128.091803]. The light production in LS detectors is by far dominated by isotropically emitted scintillation photons with no directional information, while the directional Cherenkov light is sub-dominant but preceding the scintillation light. In the CID application in Borexino, in the region of interest dominated by the signal from 0.862 MeV Be-7 solar neutrinos, the no-solar neutrino hypothesis was excluded with $>5\sigma$. This represents the first directional measurement of sub-MeV solar neutrinos as well as the first directional measurement of neutrinos in a LS detector. The novel CID method is readily applicable to next generation LS-based experiments, that will be able to perform a dedicated calibration of the Cherenkov light and thus substantially reduce the uncertainty on such measurements.

The JUNO Experiment is a neutrino experiment under construction near Kaiping city in Southern China, with planned completion in 2023. With a broad physics program, it aims to address various topics in neutrino physics and particle (astro-) physics. The design-driving main goal is the determination of the Neutrino Mass Ordering (NMO) using reactor electron anti-neutrinos from two strong nuclear power plants at a distance of about 53 km. To measure the oscillation pattern of reactor neutrinos, the main detector consists of a 20 kton LS target densely instrumented by different types of PMTs to reach a required excellent energy resolution of 3% at 1 MeV. Furthermore, to reach its goals, the JUNO detector requires a high level of radiopurity. To ensure this, the 20-ton OSIRIS LS detector will be used to monitor the radio-purity of the LS during its months-long purification and filling into the main JUNO detector [4]. This allows to give early warnings in case of an unexpected contamination of the LS due to possible air-leaks in the LS processing. Our neutrino group is responsible for the calibration of the OSIRIS detector and is involved in the development of the DAQ and analysis framework software. In addition, our group is involved in various physics analyses regarding NMO, atmospheric neutrinos [5], solar, and geo-neutrinos.

Polarized proton and deuteron beams

Within the BOB project to measure the helicity of the anti-electron neutrino via the rare β-decay $n \rightarrow H_{2s} + \bar{\nu}_e$ it is necessary to measure the occupation numbers of the hyperfine substates of these metastable hydrogen atoms. This requires separating the hyperfine α-substates with $m_j=+1/2$ from the β_3 state ($m_j=m_I=-1/2$). Thus, a Sona-transition unit was designed, built and tested that is similar to those in use at polarized proton sources to exchange the occupation numbers of the α_1 and β_3 states. Tests showed that hydrogen atoms passing through the sinusoidal magnetic fields of the Sona unit experience an oscillating magnetic field that excites transitions between the hyperfine substates with an energy difference of 10^{-8} eV and an uncertainty of +/- 10^{-11} eV. In parallel, a new type of spinfilter was designed for the BOB project that should be able to separate all four hyperfine substates of metastable hydrogen.

Outlook for 2022

- HADES: STS and Inner-TOF detection systems are ready for the proton beam time in February in which electro-magnetic transitions of excited hyperons will be investigated.
- JEDI: preparation for a beamtime in February to study the proton SCT (Spin Coherence Time).
- Borexino: updated measurement of CNO neutrinos with the final Borexino data set.
- JUNO: preparation of a JUNO paper with INFN Milano on the sensitivity to medium-energy solar neutrinos.
- OSIRIS: installation and calibration of the OSIRIS detector.
- Further improvements to the Sona-unit are expected to decrease the uncertainty down to 10^{-13} eV, allowing leading-order QED corrections to be observed [6]. This new technique, where an atom with a velocity ($v \ll c$) moves through an oscillating magnetic field to induce transitions at such tiny energy level, can in principle be applied to other atoms and molecules to establish a new type of precision spectroscopy.

Selected publications of 2021

- [1] Barucca, G. ; Davì, F. ; Lancioni, G. ; et al.: Study of excited Ξ baryons with the PANDA detector. The European physical journal / A 57(4), 149 (2021), DOI:10.1140/epja/s10050-021-00444-5
- [2] Barucca, G. ; Davì, F. ; Lancioni, G. ; et al.: PANDA Phase One. The European physical journal / A 57(6), 184 (2021), DOI:10.1140/epja/s10050-021-00475-y
- [3] Slim, J. ; Nikolaev, N. N. ; Rathmann, F. ; et al.: First detection of collective oscillations of a stored deuteron beam with an amplitude close to the quantum limit. Physical review accelerators and beams 24(12), 124601 (2021), DOI:10.1103/PhysRevAccelBeams.24.124601
- [4] Abusleme, A. ; Adam, T. ; Ahmad, S. ; et al.: JUNO sensitivity to low energy atmospheric neutrino spectra. The European physical journal / C 81(10), 887 (2021), DOI:10.1140/epjc/s10052-021-09565-z
- [5] Abusleme, A. ; Adam, T. ; Ahmad, S. ; et al.: The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS. The European physical journal / C 81(11), 973 (2021), DOI:10.1140/epjc/s10052-021-09544-4
- [6] Engels, R. ; Büscher, M. ; Buske, P. ; et al.: Direct observation of transitions between quantum states with energy differences below 10 neV employing a Sona unit. The European physical journal / D 75(9), 257 (2021), DOI:10.1140/epjd/s10053-021-00268-4

7. Research of the Theory Departments

Coordination: Prof. Dr. Hannah Elfner (JWGU Frankfurt, GSI)
Author: Hannah Elfner

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 theory activities at GSI have undergone a major restructuring in 2021. The 3 groups have been turned into 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). Those three departments together form now the 5th research pillar of GSI "Theory".

Via the hirings over the last years, the permanent personnel within the theory department consists of a nice mixture of senior and junior scientists as well as displaying a decent gender balance. The most recent new scientist, Daniel Mohler, has started his activities in 2021 and obtained a DFG Heisenberg fellowship. His research focusses on lattice QCD calculations for hadronic states and their interactions and nicely complements the effective field theory calculations of M. Lutz. Andreas Bauswein who is working on the dynamics of neutron star mergers has been tenured to senior staff scientist after a positive evaluation on 29.6.2021.

The members of the theory department are very active in obtaining third party funding, most prominently, the CRC-TR-211 on "Strong-interaction matter under extreme conditions" has started into the second funding period. The Hessian Cluster Initiative 'ELEMENTS' bringing together experts on microscopic nuclear physics (heavy-ion collisions) with the ones of macroscopic dynamic processes (neutron star mergers) has started in 2021. The interplay of experiment and theory is at the core of this program. In addition, the consortium for particle, nuclear and astrophysics within the national research data infrastructure (PUNCH4NFDI) has begun its work in the Fall of 2021 with some contributions from the GSI theory groups.

In 2021, G. Martínez-Pinedo received the highest award for scientists in Germany, the 2022 Gottfried Wilhelm Leibniz prize of the German Research Foundation for his work on understanding the formation of heavy elements within neutron star mergers and the associated kilonova. He has been also named a member of the Academia Europeae. Stefan Typel is now an 'Outstanding Referee for Physical Review C'. H. Elfner received the "Scientist of the year" award by the Gertrud and Alfons Kassel foundation at Goethe University for her excellent research and engagement in the training of young scientists.

For the future, the theory groups look forward to more workshops in presence when the pandemic allows to increase their interactions and joint activities. Improved theory to data comparisons are on their way, that allow for open sharing of the complete work flows. The main goal is to develop the theoretical tools that permit to exploit the full potential of the GSI/FAIR facility.

7.1 Hot and dense QCD matter

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

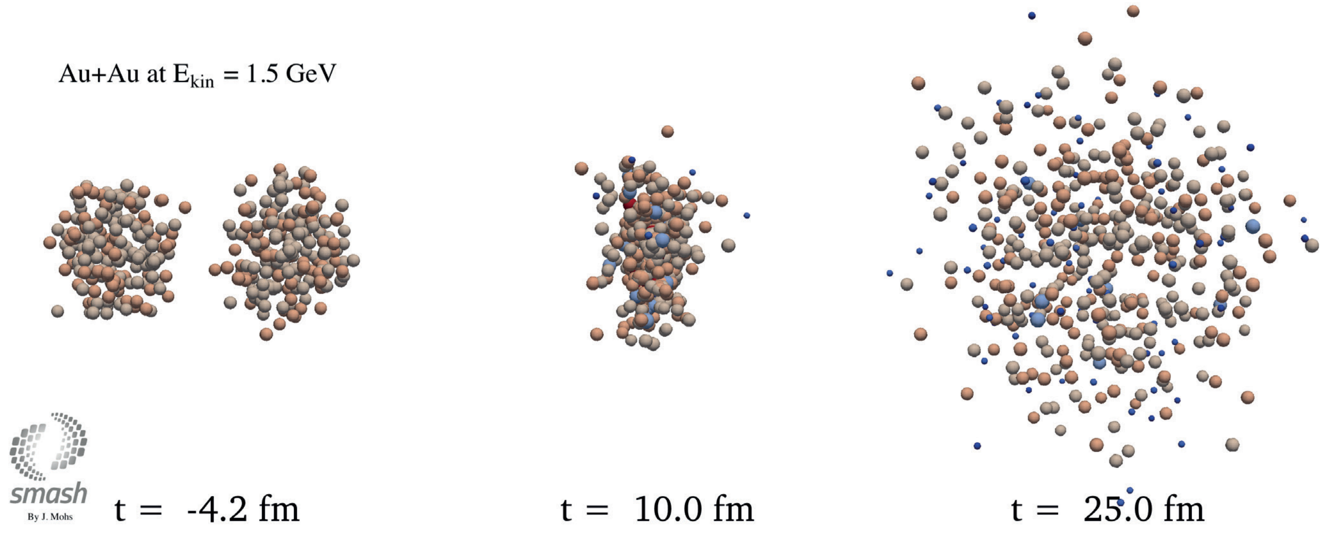

Figure 57. Visualization of a hadronic transport calculation of a gold-gold collision at 1.5 AGeV beam energy (source: J. Mohs/SMASH).

The main goal of the theory groups working on hot and dense QCD matter is to understand the dynamical evolution of heavy-ion collisions over a broad range of beam energies. For the interpretation and prediction of experimental measurements, it is crucial to provide detailed calculations that connect observables to input from quantum chromodynamics. Together with colleagues in Europe and international collaborators, sophisticated calculations based on relativistic hydrodynamics and transport theory are performed.

Highlights in 2021

Transport coefficients of hot and dense matter

One way to quantify the properties of hot and dense strongly-interacting matter is by extracting transport coefficients. The shear viscosity over entropy ratio is a measure of the momentum transport orthogonal to the direction of motion. In high-energy heavy-ion collisions the temperature dependence of shear and bulk viscosity are extracted by comparing relativistic hydrodynamic+hadronic transport hybrid approaches to experimental data. The SMASH transport approach is for example part of the NSF funded JETSCAPE collaboration that builds up a modular framework to allow state-of-the-art dynamical simulations. Employing a Bayesian model averaging technique new constraints have been obtained in [1]. Within [2] a novel constraint on the shear viscosity from low energy heavy-ion collisions has been extracted, which is shown in Fig. 2. This has been achieved by comparing a microscopic hadronic transport approach UrQMD (Ultra-relativistic Quantum Molecular Dynamics) to measurements from the HADES collaboration. This is very interesting, since the conditions at low beam energies involve a significant finite net baryon density. The dependence of transport coefficients on the net baryon chemical potential has been investigated within the dynamical quasi-particle model (DQPM) that is part of the PHSD (Parton-Hadron String Dynamics) transport approach. For this purpose, the effective dynamical quasi-particle model has been extended to large baryon chemical potentials including a critical end-point (CEP) and a 1st order phase transition. The DQPM is based on covariant propagators for quarks/antiquarks and gluons that have a finite width in their spectral functions. The thermodynamic properties match lattice QCD input where this is available and allow to calculate thermodynamics and transport coefficients in the full phase diagram [3].

Observables for medium modifications

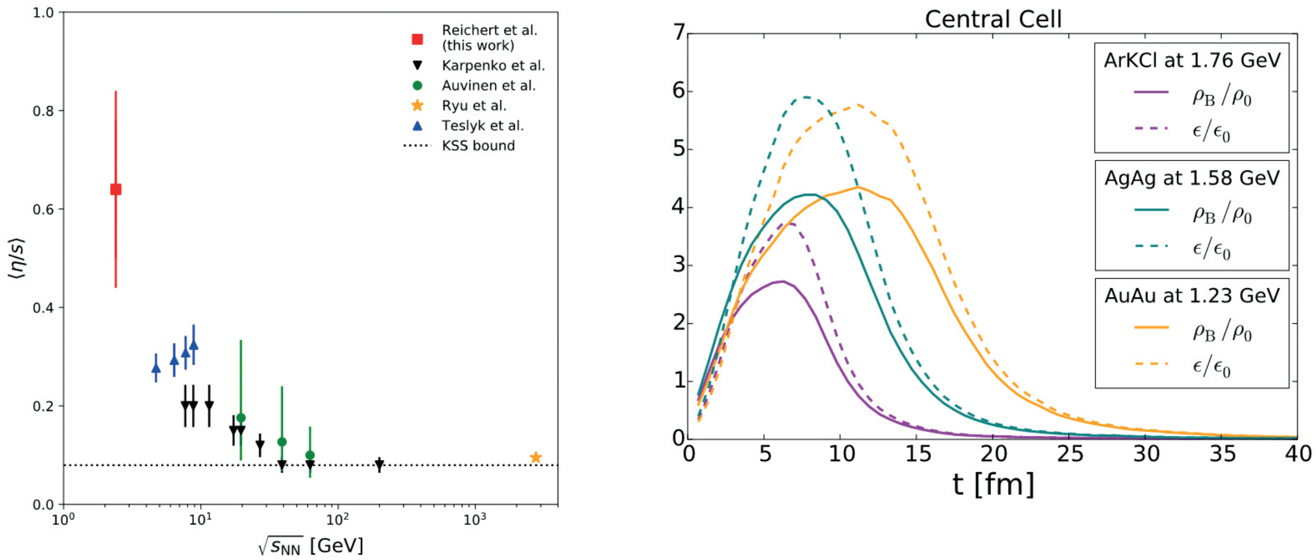

Figure 58. Left: Global summary of constraints on the shear viscosity over entropy density ratio from heavy-ion experiments, the red square depicts the newly extracted value from a comparison of UrQMD with data from HADES (taken from [2]). Right: Density reached in heavy-ion collisions under conditions studied within the HADES collaboration (here ρ_0=0.16 fm^3, ε_0=146.5 MeV/fm^3). The values have been calculated with a coarse-graining technique from the dynamical evolution of the SMASH transport approach [4].

One major goal of the heavy-ion program at GSI/FAIR is to understand the effects of the hot and dense medium formed. Figure 58 (right) indicated how large the energy density and net baryon density is within typical collision systems as they have been studied by the HADES collaboration. Several times nuclear ground state density can be reached over a significant amount of time. One observable of high interest is the dilepton emission, since electromagnetic probes escape the medium without further interactions. Surprisingly, it was found in [4] that the expected invariant mass distribution of dileptons is very similar in AgAg collisions at 1.58 AGeV to the one already observed in AuAu collisions at 1.23 AGeV. The higher beam energy seems to compensate for the smaller size of the system. Within [4] predictions for strangeness production in AgAg reactions are also made to provide guidance for the expected HADES measurements. In particular, it will be interesting to see, if the high Xi baryon production that was observed in other systems will be confirmed. In the SMASH calculation, the assumption is to produce the Xi's by high mass resonances. In [5] the in-medium effects on strangeness production (kaons, antikaons and hyperons) at SIS energies have been studied within the PHSD approach. The in-medium modifications of the antikaon properties were described via the self-consistent coupled-channel unitarized scheme (G-matrix) based on a SU(3) chiral Lagrangian which incorporates explicitly the s− and p− waves of the kaon–nucleon interaction and by the density dependent potential for kaon properties. Over a large range of beam energies very good agreement can be obtained and a clear connection of subthreshold strangeness production to medium modifications is possible.

Outlook for 2022

One topic of high interest is the formation of light clusters in heavy-ion collisions. At low beam energies, a large fraction of the baryonic content of the system is bound in clusters in the final state. There are two major concepts explaining the formation of light clusters, namely thermal production or production by coalescence in phase-space. Within the hot and dense QCD matter department several microscopic approaches to understand the formation of clusters like deuterons, helium or triton are developed. In this context, the treatment of multi-particle reactions is of relevance as well. In the Fall of 2022 a retreat of the Helmholtz Research Academy Hesse for FAIR is planned to allow for in-depth discussions and synergies with the partners at the other universities.

Selected publications of 2021

- [1] Everett, D. ; Ke, W. ; Paquet, J.-F. ; et al.: Phenomenological Constraints on the Transport Properties of QCD Matter with Data-Driven Model Averaging. Physical review letters 126(24), 242301 (2021), DOI:10.1103/PhysRevLett.126.242301
- [2] Reichert, T. ; Inghirami, G. ; Bleicher, M.: A first estimate of η/ in Au+Au reactions at E_{lab} = 1.23 AGeV. Physics letters / B 817, 136285 (2021), DOI:10.1016/j.physletb.2021.136285
- [3] Soloveva, O. ; Fuseau, D. ; Aichelin, J. ; et al.: Shear viscosity and electric conductivity of a hot and dense QGP with a chiral phase transition. Physical review / C 103(5), 054901 (2021), DOI:10.1103/PhysRevC.103.054901
- [4] Staudenmaier, J. ; Kübler, N. ; Elfner, H.: Particle production in AgAg collisions at E_{Kin} = 1.58 A GeV within a hadronic transport approach. Physical review / C 103(4), 044904 (2021), DOI:10.1103/PhysRevC.103.044904
- [5] Song, T. ; Tolos, L. ; Wirth, J. ; et al.: In-medium effects in strangeness production in heavy-ion collisions at (sub)threshold energies. Physical review / C 103(4), 044901 (2021), DOI:10.1103/PhysRevC.103.044901

7.2 Hadron physics and QCD

Head: Matthias F. M. Lutz (TU Darmstadt, GSI)
Authors: M. F. M. Lutz and D. Mohler

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

Highlights in 2021

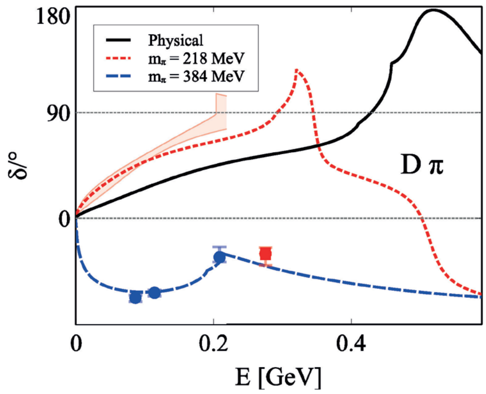

Figure 59. The s-wave D π phase shift with (I,S) = (1/2,0) at different light-quark masses. The black-solid, red-dotted and blue-dashed curves represent our predictions at physical quark masses and on two HSC ensembles with m_π = 218 MeV and m_π = 384 MeV respectively. The blue (red) bands are the lattice data on the m_π = 384 MeV (m_π = 218 MeV) ensemble of HSC. The blue (red) points are the lattice data on the m_π = 384 MeV ensemble included (excluded) in our fit.

The Hadron Spectrum Collaboration (HSC) presented new results on two of their ensembles for s-wave scattering phase shifts in the open-charm sector of QCD. For such ensembles we have made predictions that are based on the chiral Lagrangian that were published two years ago. In Figure 59 we confront our phase shifts with those of HSC. A remarkably consistent picture emerges. In particular there is mounting evidence for the existence of a flavor-sextet state in the D-π and D*-π channels, that show a striking quark-mass dependence.

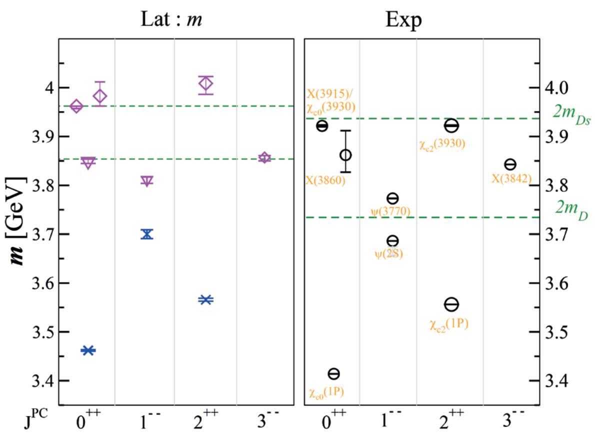

Figure 60. Masses of charmonium-like states with isospin zero from a lattice simulation (left) compared to experiment (right). The magenta symbols correspond to hadrons extracted via the scattering analysis on the lattice: diamonds represent resonances and triangles represent bound states; the blue crosses are extracted directly from the lattice energies. The experimental spectrum is taken from the PDG, where χ_{c0} (3930) and X (3915) are now identified as the same state.

In a recent publication charmonium-like resonances and bound states with various quantum numbers have been determined through (coupled-channel) scattering of D and Ds mesons. The results for quantum numbers J^{PC}=0^{++}

suggest three charmonium-like states in addition to the well-established χ_{c0} (1P): a so far unobserved bound state just below DDbar threshold, a conventional resonance likely related to χ_{c0} (3860)/ χ_{c0} (2P) and a narrow resonance just below the D_sD_s bar threshold with a large coupling to D_sD_s bar likely related to χ (3915)/ χ_{c0} (3930). These states result for unphysical quark masses and their existence has to be affirmed by exploring their quark-mass dependence. In addition, further scattering channels and by more general fit models for the scattering amplitudes are required.

Outlook for 2022

For 2022 we plan to focus on scattering observables in open-charm systems. On the Lattice QCD side novel results will be established on the gauge field ensembles generated by the CLS consortium. That will further scrutinize the quark-mass dependence of such phase shifts and shed more light on the possible existence of exotic hadronic states in this sector of QCD. On the EFT side, a thorough analysis of the published s- and p-wave phase shifts by the Hadron Spectrum Collaboration (HSC) is planned. The results will lead to predictions that can be tested in hadron physics experiments and in ongoing Lattice QCD simulations.

Such studies in the open-charm systems pave the way towards corresponding challenges in meson-baryon systems with strangeness as will be copiously be produced in day one experiments at PANDA.

Selected publications of 2021

- [1] Guo, X.-Y. ; Heo, Y. ; Lutz, M. F. M.: From lattice QCD to predictions of scattering phase shifts at the physical point, (2021), Preprint arXiv:2107.12284
- [2] Guo, X.-Y. ; Lutz, M. F. M.: Chiral excitations of open-beauty systems. Physical review / D 104(5), 054035 (2021), DOI:10.1103/PhysRevD.104.054035
- [3] Prelovsek, S. ; Collins, S. ; Mohler, D. ; et al.: Charmonium-like resonances with $J^{PC} = 0^{++}, 2^{++}$ in coupled $\bar{D}D$, $D_s\bar{D}_s$ scattering on the lattice. Journal of high energy physics 2021(6), 35 (2021), DOI:10.1007/JHEP06(2021)035

7.3 Nuclear astrophysics and structure

Head: Prof. Dr. Gabriel Martínez-Pinedo (TU Darmstadt, GSI)
Authors: Almudena Arcones, 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 2021

Gravitational waves and neutron star constraints

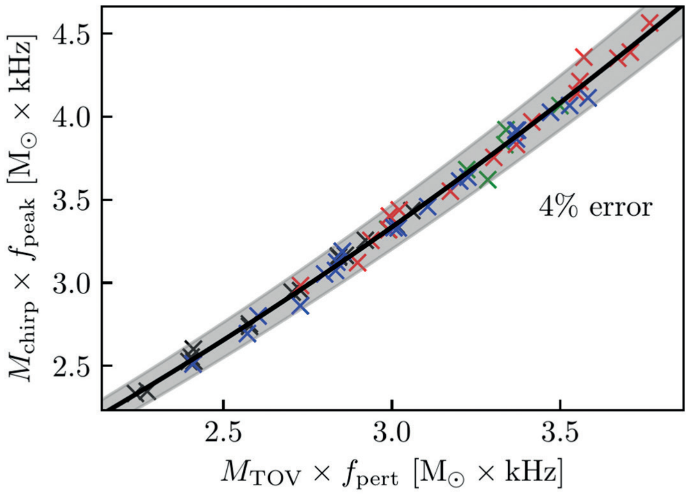

Figure 61. Universal relation between gravitational wave frequencies of isolated neutron stars and neutron star merger remnants occurring when frequencies are rescaled by the respective mass.

Stellar abundance observations are of fundamental importance to understand the enrichment of our galaxy on heavy elements by the r-process. However, these observations are limited to elemental abundances. An alternative method is the study of abudances on meteorite that provide access to isotopic ratios. Particularly important are long lived isotopes produced by the r-process. A recent study [5] has shown that ^{129}I and ^{247}Cm can be used to constraint the enrichment of our solar system by r-process events and in particular the nature of the astrophysical site from which the material originates (see Figure 61). However, such determination will require improved nuclear physics data and calls for future experiments at FAIR.

Nucleosynthesis heavy elements by the r-process

One of the main goals of the NuSTAR program at GSI/FAIR is the study of the nucleosynthesis of heavy elements by the r-process. A comprehensive review addressing the astrophysical, experimental and theoretical aspects relevant to the r-process has been published in Reviews of Modern Physics [3]. Weak interaction processes play a fundamental role in the dynamics and shaping the nucleosynthesis conditions under which the r-process operates. A review discussing recent experimental and theoretical advances in the description of electron capture processes and their impact on our understanding of various astrophysical objects has been published [K. Langanke, G. Martínez-Pinedo, and R. G. T. Zegers, Reports Prog. Phys. 84, 066301 (2021)]. The high densities and temperatures reached in astrophysical environments and in particular neutron star mergers lead to the production of large amounts of neutrinos. Those neutrinos suffer flavor oscillations that may have an important impact on the nucleosynthesis. Recently a novel mode of oscillation denoted fast oscillations has been discovered in which the oscillations are driven by anisotropies in the neutrino flux. A method to study the stationary solutions for a dense neutrino gas has been presented [Z. Xiong and Y.-Z. Qian, Phys. Lett. B 820, 136550 (2021)]. Within another study [4] the output of merger simulations was employed

DOI:10.15120/GSI-2022-00454

to study fission reactions during the rapid neutron capture process. This work addressed the regime where fission becomes important, and it quantified the impact of fission yields on the final abundance distribution of nuclei being produced by the r-process.

Kilonova light curves and spectra provide a unique opportunity to study the in-situ operation of the r-process and learn about the dynamics of the ejected material. In order to benchmark the capabilities of current radiative transfer codes to reproduce spectral features and obtain properties of the astrophysical environment, we have performed a probabilistic reconstruction of the type Ia supernova explosion parameters using machine learning techniques [J. T. O'Brien, W. E. Kerzendorf, A. Fullard, M. Williamson, R. Pakmor, J. Buchner, S. Hachinger, C. Vogl, J. H. Gillanders, A. Flörs, and P. van der Smagt, Astrophys. J. Lett. 916, L14 (2021)].

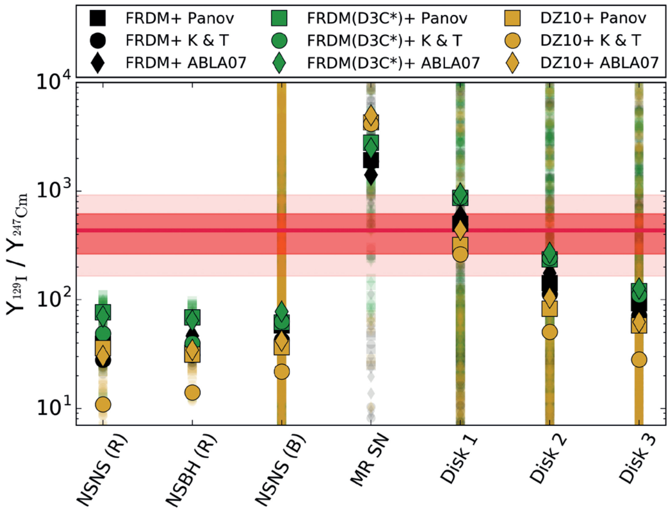

Figure 62. ^{129}I/^{247}Cm abundance ratios predicted by theoretical r-process models. The symbols denote the use of different nuclear physics inputs and astrophysical scenarios. The horizontal red solid line shows the meteoritic ratio, and the shaded bands are its 1σ and 2σ uncertainties.

Stellar abundance observations are of fundamental importance to understand the enrichment of our galaxy on heavy elements by the r-process. However, these observations are limited to elemental abundances. An alternative method is the study of abudances on meteorite that provide access to isotopic ratios. Particularly important are long lived isotopes produced by the r-process. A recent study [5] has shown that ^{129}I and ^{247}Cm can be used to constraint the enrichment of our solar system by r-process events and in particular the nature of the astrophysical site from which the material originates (see Figure 62). However, such determination will require improved nuclear physics data and calls for future experiments at FAIR.

Outlook for 2022

One of our main goals is to develop a complete theoretical pipeline that combines astrophysical simulations, nuclear physics input, nucleosynthesis modeling and radiation transport to predict nucleosynthesis yields and electromagnetic signals associated to sites where the r-process operates. For 2022, we expect to develop a complete database of atomic opacities for elements heavier than iron. This will constitute the basics to develop kilonova spectral models and will allow to identify key properties that can be measured at FAIR.

Selected publications of 2021

- [1] Bauswein, A. ; Blacker, S. ; Lioutas, G. ; et al.: Systematics of prompt black-hole formation in neutron star mergers. Physical review / D 103(12), 123004 (2021), DOI:10.1103/PhysRevD.103.123004
- [2] Lioutas, G. ; Bauswein, A. ; Stergioulas, N.: Frequency deviations in universal relations of isolated neutron stars and postmerger remnants. Physical review / D 104(4), 043011 (2021), DOI:10.1103/PhysRevD.104.043011
- [3] Cowan, J. J. ; Sneden, C. ; Lawler, J. E. ; et al.: Origin of the heaviest elements: The rapid neutron-capture process. Reviews of modern physics 93(1), 015002 (2021), DOI:10.1103/RevModPhys.93.015002
- [4] Lemaître, J.-F. ; Goriely, S. ; Bauswein, A. ; et al.: Fission fragment distributions and their impact on the r -process nucleosynthesis in neutron star mergers. Physical review / C 103(2), 025806 (2021), DOI:10.1103/PhysRevC.103.025806
- [5] Côté, B. ; Eichler, M. ; Yagüe López, A. ; et al.: 129I and 247Cm in meteorites constrain the last astrophysical source of solar r-process elements. Science / Science now 371(6532), 945 - 948 (2021), DOI:10.1126/science.aba1111

8. Collaborations & cooperations

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

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

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

HGS-HIRe conducts structured doctoral training in all research fields of GSI and FAIR since 2008. In addition to high level educational measures, the graduate school provides individual advice and support as contact and care center within the framework of its structured doctoral program. By the end of 2021, more than 320 doctoral researchers, who perform their research on GSI-FAIR related topics, are counted as participants in the HGS-HIRe program. Furthermore, nearly 50 doctoral researchers affiliated to HGS-HIRe finished successfully their doctoral projects and theses in 2021. In order to foster the role of HGS-HIRe within GSI-FAIR, the governance structure of the graduate school has been transformed in favor of an improved involvement in the organizational structure of GSI-FAIR and updated appointments of the HGS-HIRe Management Board as well as the Application Review Committee of HGS-HIRe since 2020. This transformation process has been concluded in large part by the end of 2021 and all panels of the graduate school fully resumed their work.

However, the heavy impact of the ongoing COVID-19 pandemic on the HGS-HIRe program was and still is a challenge. In view of the difficult Corona situation, HGS-HIRe constantly kept the participants informed about related advisory offers and services at GSI-FAIR and the partner universities as well as internal and external online courses and training events. Among these measures, the HGS-HIRe supervision and care concept including the individual thesis advisory committees and specially tailored educational measures proved its value once more. In addition, the virtual (online) concepts developed by HGS-HIRe in the previous year 2020 to maintain important parts of the graduate school's contact and care offers and the training program have been enlarged in 2021.

Particularly the number of highly interactive HGS-HIRe Transferable Skills Courses, that have very successfully been transformed into pure online training events over the year 2020, has been more than doubled in 2021. These training events are designed as an integrated series of three consecutive courses combining different aspects of professional and personal development in a research environment and beyond. Altogether 14 online transferable skills courses with a total of nearly 300 participants have been organized and conducted by HGS-HIRe together with trainers from Great Britain in 2021. As a remarkably positive side effect the transformation of these courses into online training events and the enlarged offer further strengthened the opportunity to open these courses for participation of doctoral researchers from other Helmholtz Graduate Schools leading to a more interdisciplinary group structure and learning environment and, moreover, a further strengthening of the Helmholtz-wide network and spirit. This development is clearly appreciated by the participating doctoral students as shown by their very positive feedback on these courses.

Regarding the scientific training, HGS-HIRe was able to improve the corresponding event offers compared to the previous pandemic year. The annual HGS-HIRe & RS-APS Lecture Week on Atomic, Laser and Plasma Physics has been jointly organized and offered together with the Research School of Advanced Photon Science (RS-APS) at the Helmholtz-Institut Jena as an improved, more interactive online event in October 2021. In order to attract doctoral researchers from more diverse fields of research, this lecture week was scientifically dedicated to the more general topic "Novel Applications Triggered by Modern Laser Technologies". Furthermore, external online 'power weeks', i.e. training events on more specialized scientific and technical aspects and methods, as the "Helmholtz Herbst Hackathon", the "Artificial Intelligence Symposium on Application, Theory and Research (AI-STAR)", and 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.

Moreover, the following supportive information and training events complemented the program offers in 2021: Frequent online HGS-HIRe Information & Contact Sessions for participants, online event offers of the Helmholtz Open Science Office, HGF online workshops "Young Entrepreneurs in Science" and "Start-up Day 2021", and the online "HEPTrepreneurs episodes" by HEPTech in collaboration with the Technology Transfer (TT) Divisions at GSI and CERN.

In summary, HGS-HIRe took the overall challenging situation of the second COVID-19 pandemic year as a chance to strategically foster its structured program offers by advancement of online training and supportive information events as well as by further strengthening its networking within the Helmholtz community. This will have not only a positive impact on the HGS-HIRe program under the still ongoing Corona situation but also on the activities of HGS-HIRe in the post-pandemic future when combinations of well-established residential training events, as e.g. HGS-HIRe lecture/power weeks and the International Summer Student Program at GSI-FAIR, and successfully implemented online offers are intended in order to substantially increase the variety of attractive program elements for the HGS-HIRe participants and young researchers interested in the excellent GSI-FAIR research and training environment.

8.2 ExtreMe Matter Institute EMMI

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

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

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

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

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

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

Highlights in 2021

Exploring applications of holographic duality to real-world superfluids

The theoretical description of strongly coupled many-particle quantum systems poses a great challenge. Holographic duality provides a promising new approach by mapping strongly coupled field theories to weakly coupled gravitational theories with an additional dimension of space. This duality translates the behavior of thermal quantum systems to the physics of black holes. In the past 20 years, tremendous progress has been made in constructing such higher-dimensional models to describe a wide variety of physical phenomena at strong coupling, ranging from nuclear physics to condensed matter physics. It is intrinsically difficult, however, to determine the dynamical parameters of the strongly coupled systems described by the dual gravitational theories, and thus to identify the materials and physical situations to which the dual theories apply. A new work now finds evidence that a concrete gravitational model can describe strongly dissipative vortex dynamics in real-world superfluids. The new method proposed here is to use a dynamical process for determining the phenomenological parameters of the holographic theory. Specifically, a vortex and an antivortex moving in a two-dimensional superfluid, or in other words, a pair of counterrotating quantum eddies is considered. Their mutual approach and annihilation is precisely measured and compared to phenomenological descriptions. This allows one to quantify the dissipation of a vortex in the superfluid with the corresponding friction parameters. The results indicate that the holographic description indeed applies to vortex dynamics and turbulence in strongly dissipative superfluids. The study suggests in particular that experiments with ultracold atomic Bose gases or thin helium films can test predictions obtained by means of the holographic duality in a regime well beyond the reach of conventional theoretical methods. [P. Wittmer et al., Vortex Motion Quantifies Strong Dissipation in a Holographic Superfluid, Phys. Rev. Lett. 127(10), 101601 (2021) DOI:10.1103/PhysRevLett.127.101601]

EMMI events in 2021

EMMI Workshop "Experimental and theoretical status of and perspectives for XYZ states", Organizers: F. Nerling, C. Hanhart, April 12-15, 2021, online

ECT*-EMMI/GSI Workshop "Nuclear Physics Meets Condensed Matter: Symmetry, Topology, and Gauge", Organizers: A. Gezerlis, A. Roggero, C. Sa de Melo, July 19-21, 2021, ECT*, Trento, Italy

EMMI RRTF "Real and virtual photon production at ultra-low transverse momentum and low mass at LHC", Part 1 - Online Workshop, Organizers: S. Flörchinger, K. Schweda, R. Bailhache, September 13-14, 2021, online

EMMI Workshop "New avenues for the low-energy NUSTAR program at GSI-FAIR", Organizers: T. Dickel, J. Gerl, W. Korten, September 16-17, 2021, GSI, Darmstadt / online

EMMI Workshop "Interdisciplinary Workshop on Supersolidity", Organizers: F. Ferlaino, A. Recati, S. Stringari, September 20-22, 2021, Trento, Italy

ECT*-EMMI/GSI Workshop "Exploring high-muB matter with rare probes", Organizers: E. Scomparin, R. Rapp, G. Usai, M.P. Lombardo, T. Galatyuk, October 11-15, 2021, Trento, Italy

Selected publications of 2021

- [1] Andronic, A. ; Braun-Munzinger, P. ; Köhler, M. K. ; et al.: The multiple-charm hierarchy in the statistical hadronization model. Journal of high energy physics 2021(7), 35 (2021), DOI:10.1007/JHEP07(2021)035
- [2] Andronic, A. ; Braun-Munzinger, P. ; Gündüz, D. ; et al.: Influence of modified light-flavor hadron spectra on particle yields in the statistical hadronization model, DOI:10.1016/j.nuclphysa.2021.122176
- [3] Braun-Munzinger, P. ; Friman, B. ; Redlich, K. ; et al.: Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements. Nuclear physics <Amsterdam> / A 1008, 122141 (2021), DOI:10.1016/j.nuclphysa.2021.122141
- [4] Ewerz, C. ; Samberg, A. ; Wittmer, P.: Dynamics of a vortex dipole in a holographic superfluid. Journal of high energy physics 2021(11), 199 (2021), DOI:10.1007/JHEP11(2021)199
- [5] Wittmer, P. ; Schmied, C.-M. ; Gasenzer, T. ; et al.: Vortex Motion Quantifies Strong Dissipation in a Holographic Superfluid. Physical review letters 127(10), 101601 (2021), DOI:10.1103/PhysRevLett.127.101601

9. Accelerator operations and operation of the infrastructure support

Interims head: Dr. Udo Weinrich
Author: Udo Weinrich

In May 2021, the former head of accelerator operation Prof. Dr. Mei Bai left GSI and her role of the head of the business area accelerator operations was taken over by Dr. Udo Weinrich on an interim basis.

In 2021 the business area accelerator operations (ACC) successfully carried out the physics run in the first half of the year and shutdown activities in the second half of the year to prepare the beam time 2022. In addition, ACC continued its effort to contribute to the various FAIR project tasks well as leading the upgrade program of the existing GSI accelerator facility.

The COVID-19 pandemic situation imposed quite some constraints to the daily work. Nevertheless, the user beam time could be carried out in full. Concerning the physics run for the first time after 5 years uranium beam could be delivered. In addition, new beam modes and improved intensities of several ion beams could be achieved. Another remarkable feature was the high number of experiments being able to take beam in parallel. Finally it has to be mentioned that there was further progress in the CRYRING@ESR operation using ESR beams.

Also most of the repair and maintenance work in the shutdown could be made according to schedule. Water and vacuum leakage appearing during the shutdown on several aged devices in the UNILAC led, however, to the situation that not all repairs could be terminated prior to the beam time 2022. One example is the tunnel septum which directs the beams towards the X-,Y- and Z-branches of the UNILAC experimental hall. Directing the beam into the Z-branch is at the moment not possible. Luckily no experiments were planned here during the 2022 beam time and the tunnel septum should be repaired for the beam time 2023.

Great progress was made in the upgrade project for the UNILAC post-stripper. The First of Series of the new acceleration sections was successfully copper coated, completely assembled and until the end of the year also commissioned with RF power. All design parameters for RF voltage and power could not only be reached, but even significantly exceeded. This comes together with the successful integration and power test of a quadrupole magnet into a drift tube. Therefore, all major technical challenges for the production of the new accelerating structure for the post-stripper are now under control. Consequently, this project is now starting the phase of series components procurement.

ACC also continues its commitments to the FAIR project in leading the work packages of the p-Linac proton source, p-Linac RF as well as for the stochastic cooling for the Collector Ring (CR). The ACC units galvanic workshop, the mechanical workshop and technology laboratory supported the design, construction and integration of many FAIR components – especially for the p-Linac and the SIS100 dipoles. Another important step forward was the establishment of the FAIR subproject “FAIR-commissioning” under the leadership of the business area ACC. Commissioning scope and phases were defined as well as the basic organisational procedures. Planning of the tasks has started.

Other upgrade measures for the existing facility as well as progress on the cw-Linac advanced demonstrator have also been achieved.

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

9.1 User beam time

9.1.1 Beam operation – performance and availability

Authors: M. Vossberg, O. Geithner, M. Klich

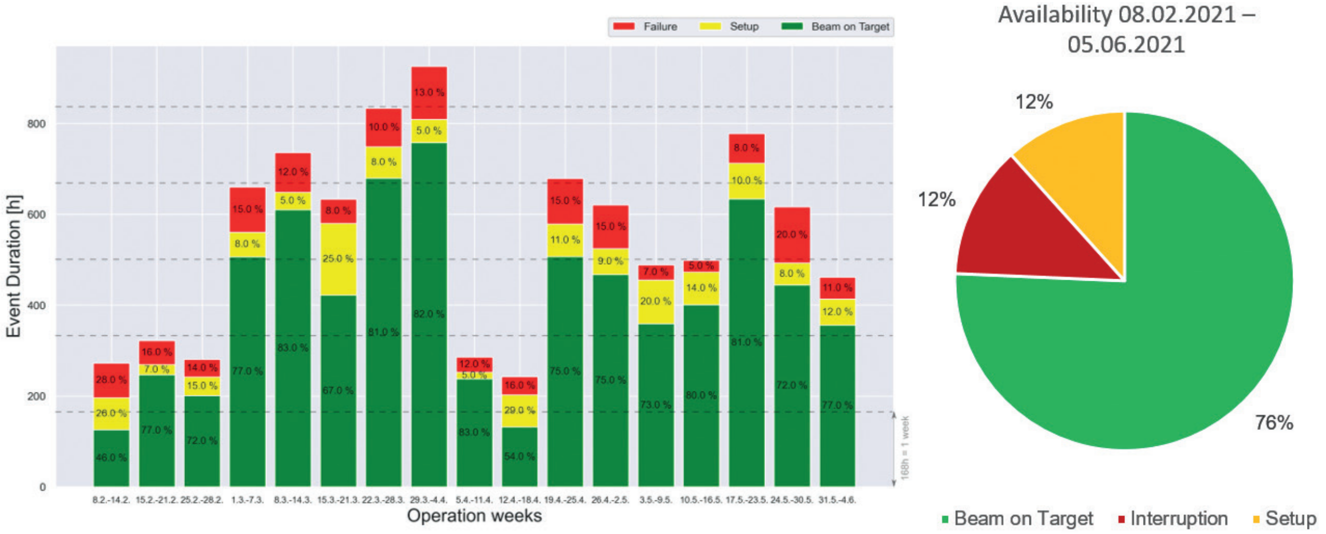

Figure 63. The diagram (left) shows the individual weeks of the 2021 experimental beam time with the event duration. The colors stand for Beam on Target, Setup, and Failure respectively. Each of the dashed lines represents a period of one week. For experiments running in parallel, the integral time increases accordingly. In the last week of March, there was a maximum of more than five experiments in parallel operation. The parallel factor over the entire experiment beam time is 3.3 and was significantly higher in this beam time than in previous years. The right picture shows the overall availability for the experimental beam time.

The fourth Physics Run within the FAIR Phase-0 started on February 8th, after a conditioning period for the UNILAC-HF of 3 weeks and a short recommissioning phase. The Experimental beam time ended on June 5th, followed by machine beam time until July 16th. During the beam time, a total of 15 different types of ions were accelerated and delivered to the experiments. A significant part of the beamtime was the 50 days uranium block, where different experiments have been supplied with beam in the caves HTA, HTC, FRS, ESR, and CryRing behind the SIS18 as well as UNILAC Material Research branch, an experiment area behind the UNILAC. In parallel, there was a Calcium beam for the UNILAC experiments in X8, Y7, and M1-3 and a xenon beam provided for the FRS. For the planned test of the First Of Series of the new ALVAREZ structure, the ALVAREZ 4 was switched off from the beginning of May, so the maximum energy from the UNILAC was limited to 8.6 MeV. The different experiments with the most diverse requirements ensured a very busy beam schedule with an average parallel operation factor of 3.3 (Figure 63). This required many new settings and adjustments to the machine over the entire period. However, one of the biggest challenges in this beam time was the Corona pandemic. Because of the Corona pandemic, there were special security measures in the main control room (HKR), such as compulsory masks, disinfectants, distance, limited access, and no visitors. The increased number of people in the home office led to a reduction of communication channels, also because of limited telephone availability. The very ambitious and packed beam schedule also ensured that the majority of the operators were continuously scheduled into rotating shifts for 6 months without a break. The successful beam time was delivered in the end due to the very high motivation and flexibility of the specialist groups and our operators.

Another highlight is the accelerator's achievements. For example, the nominal intensities of some ion types were exceeded, leading to better statistics for the experiments. For the first time after 5 years, an operation employing uranium has provided beam to the users and the full path from UNILAC to SIS18 and via ESR to CRYRING was operated for the first time. During this beam time, new or re-established operation modes have been implemented. An improvement in ion source stability resulted in a longer lifetime and fewer interruptions. For the first time, a parallel operation of four different types of ions could be established, and high current carbon and proton beam could be provided in parallel from one ion source. A new HSI-RFQ working point was defined, to assure operation stability for uranium operation with a good transmission. For the SIS18, a chimney function for all beam paths was implemented to achieve better parallel performance for the users. A new RF system allows SIS18 routine operation with reduced injection energy from UNILAC to the highest possible extraction rigidity. In the high-energy beam path, the beam-line optics were improved and a new beam path from the SIS18 via the FRS to the cave HTM was commissioned.

The total time of all ongoing experiments in parallel operation mode was about 9200 hours. Overall availability of 88% was reached for the experimental beam time. During this time 76% of the beam was successfully delivered to the users with an average downtime of 12% (1100h). The longest interruptions were caused by the kicker GS04MK1E with 130 hours (a bug fix of internal modules was necessary), by the TK sweeper problems due to multiple interdependent causes (90 hours), by the dipole TK4MU4 vacuum leak (80 hours), and by the insulation of the Penning Ion Source, which was completely damaged with consequential failures (80 hours) and the vacuum leakage of the faraday cup GE02DC1VP (50 hours).

The availability of the operation group during beamtime has been very important: the discussions led by the group on all the encountered problems have helped to reach a better understanding of each failure and to find out the root causes. At the end of the beamtime, each expert group discussed a summary of the failures to elaborate on possible improvements.

9.1.2 Ion sources operation report

Authors: R. Hollinger, A. Adonin, R. Berezov, F. Maimone, K. Tinschert

Ion species	Duty Cycle*	Intensity at RFQ (emA)	Ion source	Duration (days)
$^{4}He^{+}$	Cw	0.45	ECRIS	18
$^{12}C^{3+}$	Cw	0.16	ECRIS	16
$^{15}CH_3^{+}$	1Hz / 0.5ms	2.8	MUCIS-1990	19
$^{32}O_2^{+}$	1Hz / 0.5ms	5	VARIS	29
$^{40}Ar^{+}$	1Hz / 0.8ms	11	MUCIS-2010	11
$^{40}Ar^{8+}$	Cw	0.18	ECRIS	32
$^{48}Ca^{10+}$	Cw	0.09	ECRIS	39
$^{50}Ti^{2+}$	50Hz / 5ms	0.05	PIG	24
$^{56}Fe^{2+}$	10Hz / 1ms	0.18	PIG	6
$^{78}Kr^{2+}$	1Hz / 1ms	6.5	MUCIS-2010	7
$^{78}Kr^{2+}$	5Hz / 1ms	0.12	PIG	12
$^{107}Ag^{2+}$	1Hz / 0.55ms	3	VARIS	6
$^{124}Xe^{2+}$	1Hz / 1ms	5.5	MUCIS-2010	1
$^{124}Xe^{3+}$	1Hz / 1ms	3.2	MUCIS-2010	20
$^{136}Xe^{3+}$	5Hz / 1ms	0.3	PIG	9
$^{136}Xe^{6+}$	25Hz / 5ms	0.2	PIG	4
$^{181}Ta^{3+}$	1Hz / 0.4ms	6	VARIS	6
$^{197}Au^{8+}$	25Hz / 3ms	0.04	PIG	21 (1st Block)
$^{197}Au^{8+}$	25Hz / 3ms	0.04	PIG	9 (2nd Block)
$^{208}Pb^{4+}$	1Hz / 0.4ms	6	VARIS	21
$^{209}Bi^{4+}$	1Hz / 0.4ms	10	VARIS	2
$^{238}U^{4+}$	1Hz / 0.45ms	14	VARIS	49

Table 2. Ion species delivered to the acclerator.

* The ECR-duty cycle is always 100%, the UNILAC provides in max. 50 Hz / 5ms.

In 2021 the Ion Sources department provided various types of ions for a user beam time as well as for an engineering run. The high current ion sources including Multi Cusp Ion Source (MUCIS) and Vacuum Arc Ion Sources (VARIS) from Terminal North, the Penning Ionization Gauge (PIG) ion source from Terminal South and the Electron Cyclotron Resonance Ion Source (ECRIS) from the High Charge State Injector (HLI) were supplying the UNILAC in parallel operation. Table 2 shows the different ion species delivered to the accelerator. Representatively the analyzed beam currents in front of the High Current Injector HSI-RFQ and of the HLI-RFQ, respectively are depicted.

The PIG sources provided the following ion species: $^{136}Xe^{3+}$ for HTC and $^{56}Fe^{2+}$ for the biophysics program with stable operation and a long lifetime (>70 hrs). $^{197}Au^{8+}$ beam has been provided for the material research program and $^{50}Ti^{2+}$ for direct mass measurements with SHIPTRAP and for chemical studies as well as for operator training. For $^{50}Ti^{2+}$ production the PIG source was running with maximum performance (50 Hz / 5 ms) including high temperature operation resulting in a lot of breakdowns in the extraction system, especially by increased arc power. This leaded to a less stable operation and a reduced lifetime. As a result, all new isolators made from POM-material were destroyed during this time. For the second block with gold beam from the PIG it was necessary to change all isolators which led to an 80 hours shut down. In this time $^{136}Xe^{6+}$ beam has been offered as a partly compensation. For the next beam time it is planned to change the POM isolator material to ceramic. In a second step, it is also planned to increase the enrichment of ^{50}Ti of electrodes from 10% to 15% to get an increased lifetime and a better performance.

The ECRIS at HLI provided the following ion beams: $^{4}He^{+}$ for HTC and for testing the three new Bunch-Structure-Monitors at UCW, $^{12}C^{3+}$-beam for the biophysics experiments including the FLASH experiment and $^{48}Ca^{10+}$ for the Super Heavy Element (SHE) and Material Research program. A higher intensity of $^{12}C^{3+}$ could be achieved since CH_4 has been used as main gas instead of CO_2. A reduced contamination of oxygen into the carbon beam has been observed. A $^{48}Ca^{10+}$ beam with excellent quality in terms of intensity and stability was produced. Up to 0.1 mA peak intensity has been achieved for longer time with the tungsten grid mounted in the oven head, used for the evaporation of metal elements and compounds. Higher beam stability has been ensured as well by using a diagnostic set-up based on an optical emission spectrometer. At HLI a $^{40}Ar^{8+}$ beam could be delivered to the cw-Linac Advanced Demonstrator and the ROSE emittance measurements device temporarily installed at X3.

Operation of high current ion sources (MUCIS-1990, MUCIS-2010 and VARIS) from Terminal North brought several highlights in 2021. MUCIS-1990 ion source showed high performance with methane gas producing CH^{3+} ions. With a beam current of 2.7 mA (CH^{3+}) in front of the High Current Injector (HSI)-RFQ beam intensities at the end of the UNILAC transfer channel of 3.6 x 10^{11} particles per 100 µs pulse for protons and 6 x 10^{10} particles per 100 µs pulse for C^{6+} ions, respectively could be achieved. Also a high beam availability was demonstrated during operation with methane. Total service time did not exceed 4 hours for 19 days of beamtime.

Another highlight was a seven week continuous uranium operation of VARIS source. This was the longest uranium run since 2014. A beam current of 14 mA of U^{4+} ions achieved in front of the HSI-RFQ has been resulted in beam intensities of 9 x ·10^{9} particles per 100 µs pulse for U^{73+} and 5.2 x 10^{10} particles per 100 µs pulse for U^{28+}, respectively, at the end of the transfer channel. Also for uranium beam operation a high availability of the beam was demonstrated: Only three ion source services with a total service time of 9 hrs for 49 days of the beamtime. A record ion beam availability for experiments was achieved by VARIS source in operation with lead and oxygen. The whole beamtime (21 days with Pb-208 and 29 days with O_2) has been performed with a single ion source without any service.

Due to a water leak in the 2-nd coil, the first triplet magnet (GUL4QT1) in the HSI-Low Energy Beam Transport was operated as a doublet magnet for almost 2 months. That affected the following ion beams from Terminal North: $^{78}Kr^{2+}$, $^{124}Xe^{3+}$, $^{107}Ag^{2+}$, $^{40}Ar^{1+}$, $^{209}Bi^{4+}$ and $^{32}O^{2+}$. However, in spite of a limited beam transmission between the ion source and the HSI-RFQ, it was possible to provide for the desired ion beam intensities on target owing to dedicated tuning of ion source parameters and the beamline.

9.1.3 UNILAC operation report

Authors: H. Vormann, U. Scheeler, W. Barth, M. Vossberg

In 2021 the UNILAC was in operation for 168 days of user beam time, 5 days of operator training, 3 days rf-tuning and 12 days for machine experiments. As already in 2020, there were restrictions due to the COVID-19 pandemic. Before the user beam time started, extensive Radio Frequency (RF) and beam commissioning took place. Furthermore, test periods of the High Current Injector (HSI)- RFQ with heavy ion beams ($^{238}U^{4+}$ (A/q=59.5), $^{181}Ta^{3+}$ (A/q=60.33), $^{124}Xe^{2+}$ (A/q=62)) were performed.

The beam time started with proton and carbon ($^{12}C^{6+}$) beam, generated from methane molecules CH_3 (Multi Cusp Ion Source), followed by a block of $^{208}Pb^{4+}$ (Variable Ion Source VARIS) and $^{197}Au^{4+}$ (Penning Ion Gauge PIG). UNILAC operation was then dominated by high intensity $^{238}U^{4+}$ (VARIS) beam for the synchrotron, and high duty factor $^{48}Ca^{10+}$ (ECR) beam for UNILAC users. The uranium beam was also used for machine experiments applying the pulsed hydrogen gas stripper. Uranium intensities of up to 3 emA (U^{28+}) and 1.2 emA (U^{73+}) at the end of transfer channel to the SIS18 were delivered. Unfortunately, a leakage in the vacuum chamber of the TK4MU41 dipole magnet occurred, limiting high intensity SIS18 machine experiments. The leakage could not be repaired immediately, as the approved operation time for the hydrogen gas stripper was restricted to 3 days. The leakage was repaired after the machine experiment campaign, within 5 working days.

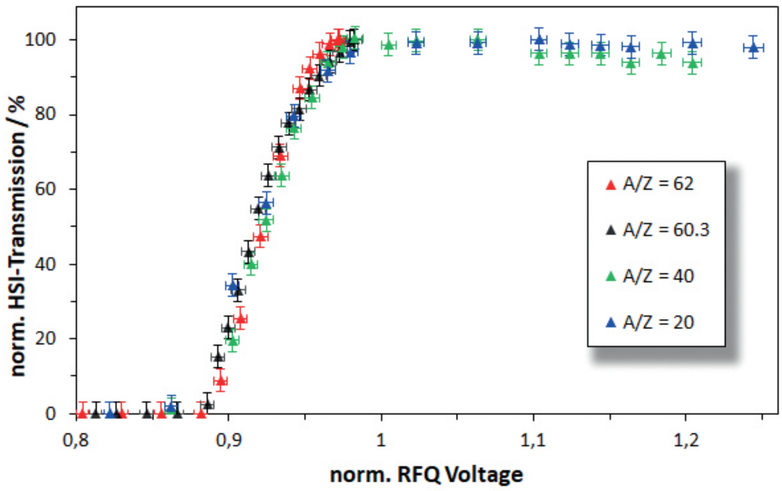

Figure 64. Transmission of the High Current Injector HSI vs. RFQ RF voltage (for different mass-over charge ratios A/q) [1].

Besides the ion species mentioned above, the High Charge State Injector ("Hoch-Ladungs-Injektor") HLI with the Electron Cyclotron Resonance Ion Source ECR delivered $^{40}Ar^{8+}$-ions for commissioning of two different Bunch Structure Monitors and the CW-LINAC cryomodule 1, for beam diagnostics machine experiments at Cave X2 and for the commissioning of the ROtating System for Emittance measurements ROSE , which is described in detail in section (TT). In addition, the HLI delivered $^{4}He^{1+}$ and $^{12}C^{3+}$ beams for further user operation.

Beam operation was suffering from various errors and interruptions: Due to a leakage the baffle plate of the dipole magnet UXCMU3 had to be operated without cooling water supply through the whole beam time. Nevertheless, the X6 beam time could still be carried out.

As planned, the 4th tank of the ALVAREZ was taken out of operation, because its RF-transmitter is being used for test operation of the First-Of-Series of the new ALVAREZ post-stripper. Several problems with the ignitrons of the RF transmitters' power supplies' fast switch-off occurred, the air ventilation system and also the roof of the RF gallery caused serious problems: rain water dropped from the roof on the HSI-RFQ transmitter and the A4 high voltage power supply.

Several incidents occured during operation:

- The transfer channel sweeper magnet power supplies TK2MW1 and TK3MW2 had severe problems with proper ramping down the coil current, interface cards were exchanged after intensive error investigations.
- After the machine experiments in April, the polarity of the HSI quadrupole quartet UH2QQ1 was reversed, resulting in improved UNILAC beam transmission. Due to a coil water leakage, the north LEBT quadrupole triplet UH4QT1 was temporarily operated as a doublet, resulting in minor additional transmission losses.
- In May an ALVAREZ 1 drift tube quadrupole had to be switched off (together with a neighbouring quadrupole) due to a coil water leakage. As the drift tube chamber cooling was not affected, RF operation went on without restrictions.
- In April the super lens showed overheating effects, after rinsing of the vessel cooling system (in May) this was cured.

9.1.4 SIS18 operation

Author: J. Stadlmann

Overview

The beam time 2021 was performed from February till July in two blocks with a short break in between. The beam time was done under COVID protocol. It was the first time with full parallel operation since introducing the new control system into regular operation.

Improvements in the control software significantly reduced the turnaround time from changing a hardware parameter till the next cycle of the machine. Only this improvement re-enabled massive parallel operation. The control system overhaul came with the price of reoccurrence of previously fixed problems for operating all ramped devices ("real-time-errors") at the beginning of the beam time. Those never completely vanished during 2021 but became bearable in the second block.

SIS18 served various experiments and machine studies. Despite the latter was massively hampered by a technical defect at the injector during the main machine study block with uranium, some machine studies could be successfully performed (see section about machine studies by P. Spiller).

SIS18 accelerated protons, helium, carbon, oxygen, argon, iron, silver, krypton, xenon, lead, bismuth, and uranium.

During the shutdown 2020-21 the faulty power supply of SIS18's electrostatic extraction septum was changed and for the first time we could operate the septum close to its nominal voltage of 160 kV. There was no previous operation experience at this field strength and initially many sparkovers hampered operation with slow extraction at high rigidities. This could be mitigated by improving the sparkover alarm and reducing losses at the septum. The higher voltages allowed much better extraction efficiencies for all high energy experiments using slowly extracted beam.

Special operation modes in 2021

During the second part of the beam time the last stage of the UNILAC (A4) was not available for operation. This reduces the injection energy for all ion species from 11.4 MeV/u to 8.6 MeV/u. The reduced revolution frequency at injection does not allow the ferrite acceleration cavities to catch the ions in four bunches (4th harmonic, H=4) as in regular operation. The frequency cannot be lowered to the required value. Previously, operation with reduced injection energy was done at the 5th harmonic (H=5), limiting the maximum extraction energy for all species at about 600 MeV/u at the upper frequency limit of the RF cavities.

The SIS18 upgrade program for FAIR involved upgrading the synchrotron's RF system with new low frequency cavities for H=2 operation. For dual harmonic operation the two systems can be synchronized. For operationing up to the maximum energy with reduced injection energy a special operation mode has been established. The ions are bunched after injection and accelerated at the beginning of the cycle with H=4 by the low frequency (H=2) cavities. They are obviously not capable of providing RF at the required frequencies during the complete ramp. The high frequency (H=4) cavities take over during the acceleration ramp and can continue acceleration to maximum extraction energy. This mode was tested before and used most of the time during the second block of 2021 if energies above 600 MeV/u where required.

Rain water leaking into the area of the main power supplies of the H=2 cavities forced a shutdown of those RF systems. An experiment running at that time required iron ions with 1 GeV/u and could initially not be continued without the use of both, H=2 and H=4 RF systems. Due to the flexibility of the new LSA based control system and the RF hardware a new cycle could be established within 4 hours. The new cycle used the H=4 cavities, bunching and accelerating ions to an intermediate flattop with H=5, de-bunching and re-bunching at H=4 there and then continuing acceleration as usual.

The bunch compressor was used for plasma physics experiments for the first time since recommissioning.

9.1.5 ESR operation and development

Authors: M. Steck, R. Heß, R.Joseph, S.Litvinov, B. Lorentz, U. Popp

The ESR storage ring delivered beams to various physics users within the scope of FAIR Phase-0 during a period of about three months in the first half of 2021. For all operational cycles the storage ring mode was used which was implemented in the previous year. For many of the requested experimental procedures it was the first time that the operation was based on the storage ring mode. As almost no dedicated time for machine commissioning and optimization was available, many of the details of the diverse experimental cycles had to be commissioned during the setup phase of the particular experiment beam time. The expenditure of time for machine tuning is still largely increased by latencies in the control system which are under investigation.

Various experiments were requiring decelerated beams, both for experiments with the decelerated beam stored in the ESR and for users of the decelerated highly charged ions after fast extraction from the ESR and transfer to CRYRING@ESR. The deceleration cycle in the ESR is not fully optimized for minimum loss. For initial intensities up to 10^7 injected ions losses during deceleration are negligible. For initial intensities exceeding 10^7 ions injected at high energy, relative loss values are observed which increase with the initial intensity, most likely caused by an increase of the occupied phase space volume with intensity. To minimize losses during the deceleration cycle dedicated machine experiments are needed, which must be supported by various diagnostics tools to measure the dependence of beam parameters on the machine parameters, both longitudinally and transversely.

Beam lifetime measurements of the stored beam with the current transformer indicate an average vacuum pressure which is significantly higher than that detected by the vacuum gauge measurements around the ring. For highly charged ions at lowest energies the vacuum conditions dominate the intensity of the decelerated ion beam delivered to the user. For beams which are decelerated to an intermediate energy the vacuum conditions are not a serious limitation, particularly if the experiment requires operation of the internal target which then determines the beam lifetime. After extensive machine tuning for experiment E125 up to 5×10^7 highly charged uranium ions could be decelerated from 300 MeV/u and stored at energies in the range of 30 to 40 MeV/u. This is slightly higher than the best intensity achieved during operation with the old control system. The experiment also benefited from reliable operation of the internal gas jet target with nitrogen over one week.

Decelerated highly charged lead and uranium ions were transferred from ESR to CRYRING@ESR. The extraction from the ESR cannot be performed with optimum conditions due to the absence of a dedicated fast kicker for extraction from the southeast corner of the ESR towards the target hall. The present extraction scheme employs a closed orbit distortion in the electron cooler section which results in a strong coupling of the ion beam extraction orbit and the conditions for electron cooling. Consequently, the two aspects cannot be optimized independently and the extraction conditions are a trade-off between optimum conditions for cooling and extraction. This conflict of tuning aspects also limits the flexibility to optimize the beam transport between ESR and CRYRING@ESR. By integration of the recently installed barrier bucket RF system into the ESR operation, the ability to extract all stored decelerated ions in a single extraction kick could be provided during the user operation with beams delivered from ESR to CRYRING@ESR. The barrier bucket RF system can be operated at frequencies down to 240 kHz which covers operation with harmonic number h=1 even for the lowest beam energies. To date the decelerated beams were transferred at an energy around 10 MeV/u. Lower energies in the ESR are possible, but due to the short lifetime of the beam at low energy, are not considered for routine operation in order to achieve best beam intensity and reduce losses at the lowest energies at the end of the deceleration cycle.

The isochronous mode of the ESR was recommissioned in 2021 with the new control system and was successfully employed for the experiment E143 in the search for nuclear decays by detection of the Schottky noise of the stored nuclei. As the ESR is operated with the new control employing a different ion optical model, the fine tuning of the non-linear magnetic components was a prerequisite for providing optimum performance of the isochronous mode. By variation of sextupole strenght, the acceptance was tuned to provide a revolution frequency according to the specific requirement of the experiment, the frequency was constant over a momentum acceptance of $\delta p/p$ = +/-0.2% to a value of $\delta f/f$ = +/- 1×10^{-5}.

The poor vacuum in the ESR needs to be addressed in the coming years by refurbishing the ESR with new sputter ion pumps. Some of the vacuum components, which are more than 30 years old will be replaced as well and investigations to identify sources of undesired outgassing or leakage are ongoing.

9.1.6 CRYRING@ESR operation report

Authors: F. Herfurth, Z. Andelkovic, S. Fedotova, W. Geithner, M. Lestinsky

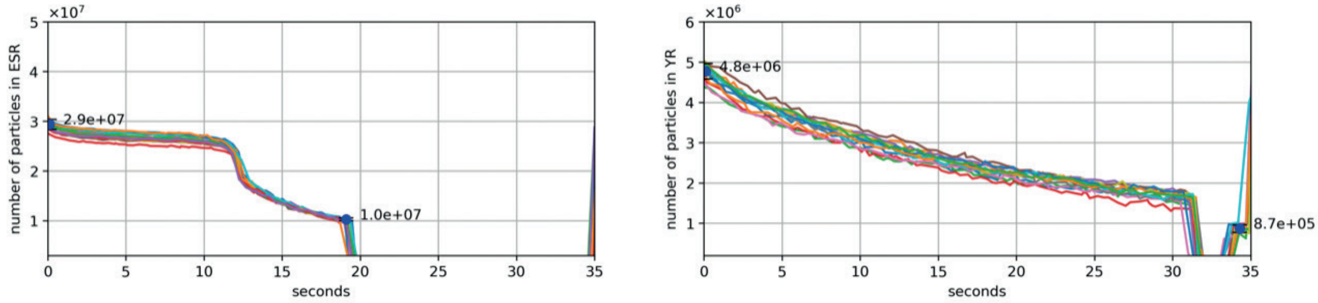

Figure 65. Transfer efficiency ESR – CRYRING@ESR (labelled with "YR") measured to 39(1) %. On the left the number of particles stored in the ESR are plotted for a number of cycles. The plot on the right-hand side shows the number of particles stored for the corresponding cycle in CRYRING@ESR. The dots with error bars give the number of particles averaged over the analyzed 14 cycles. The rightmost dot ($8.7 \cdot 10^5$ particles) measures the average background of the used parametric current transformer when there was no beam present.

The low energy storage ring project CRYRING@ESR is an in-kind contribution by Sweden to FAIR. It has been brought to GSI/FAIR in 2012/2013 and subsequently renovated, installed and recommissioned. By 2021 routine operation has been established, serving the FAIR Phase-0 physics program with heavy, highly charged ions produced in the accelerator chain via the ESR or light ions produced locally.

Seven different experiments have been served with C^+, Mg^+, O^{6+}, and Ne^{3+} beams from the local injector and Ag^{47+}, Pb^{78+}, and U^{91+} beams from ESR. For the first time, CRYRING@ESR delivered decelerated and extracted ion beams to an external fixed target experiment. Following first tests already in 2020, the Cryogenic Current Comparator (CCC) was used and thoroughly characterized also with highly-charged ions, as for instance Pb^{78+}.

Machine availability was very high, since very few interruptions were recorded that go back to failure of CRYRING@ ESR equipment. One of two longer (>1h) interruptions was due to a broken cable in the ring RF system. The other one due to impurities deposited at the extraction system of the local source. After a very cumbersome recommissioning, the electron cooler worked seamlessly at all required expansion factors up to 100 and including the cryogenic system for the superconducting magnet of the electron gun.

In 2020 the poor transfer efficiency for ions from the ESR to CRYRING@ESR turned out to be a major deficit. After a thorough analysis four steps were identified to improve, which have been realized in the preparation of the run 2021: A new Faraday cup helps identifying the location of losses, a dedicated machine beam time was used to understand and improve tuning of the HEST beam line, the four bunches in the ESR were successfully rebunched into one and finally the extraction kick was synchronized with the ESR ring RF. The result, shown in Figure 65, is a transfer efficiency about 10 times higher than in 2020, reaching about 40%.

In 2021, we also investigated the lower sensitivity limit for reliable beam setup with ions from the local injector. Compared to injection at high energy, i.e. from the ESR, the low energy injection from the local source and injector needs more charges injected to counteract the beam instrumentation sensitivity, which in general decreases with decreasing energy of the stored beam. It was found that we need at least $1.5 \cdot 10^6$ elementary charges q to be stored at the energy of the local injector in order to setup and fine tune a cooled beam accelerated to any target energy. Including the also measured transfer efficiency from the local source into the ring, an ion source needs to produce about $7 \cdot 10^6$ q mass separated to establish an in-ring experiment. Possible improvements are a better working multi-turn injection scheme and a reduced momentum spread, both of which increase the injection efficiency.

Efforts to improve the vacuum conditions focussed in sections 05 to 08 adding a new ion getter pump and NEG coating to some accessible parts before the run in 2021. The result was a slight improvement to about half the previous pressure in those sections. Beam lifetimes of 27 s for Pb^{78+} and 10 s for U^{91+}, both at 10 MeV/nucleon, have been measured. During those measurements on March-6 and May-1 the average ring pressure was measured to 6.4 and $8.1 \cdot 10^{-11}$ mbar, respectively. The highest pressure is generally observed in the electron cooler region, which will be addressed during the major repair work in the upcoming 2022 shutdown.

Apart from minor routine maintenance work, the shutdown was used to equip section 09 with the devices required for the scheduled 2022 experiments. The local teams together with the involved collaborations installed a detector chamber (CARME), a gas target chamber, and the interaction chamber for a transverse electron target. After bakeout, the vacuum pressure is back to the values before this substantial change.

The year ended with a dry run to re-establish the function of the ring with all its subsystems. Unfortunately, the local ECR ion source's magnet and chamber assembly failed fatally. While a new chamber and magnet are produced, a somewhat smaller ECR ion source has been temporarily installed (another loan from the Justus-Liebig-University in Gießen). This source was started up successfully and the first beam was also used to test the new beam position monitoring.

9.1.7 HITRAP: towards decelerator re-commissioning and in-trap electron cooling

Authors: Z. Andelkovic, F. Herfurth

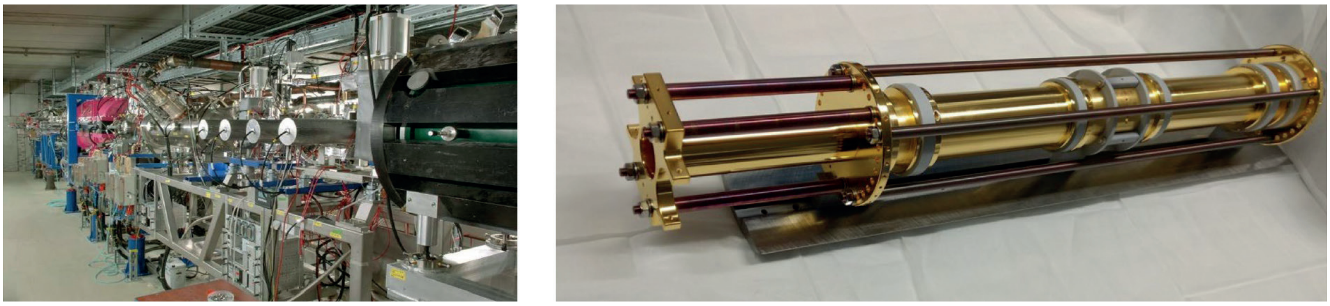

Figure 66. The HITRAP linear decelerator (left) with the redesigned Penning trap (right) as the final cooling stage.

With the ESR and the CRYRING@ESR storage rings successfully serving experiments in the recent years, HITRAP is the only remaining facility for stored and cooled ions not yet available for experiments, due to the lack of necessary resources. However, in line with the very positive developments regarding to the storage rings, GSI/FAIR decided to support the recommissioning of the HITRAP decelerator. Consequently, the necessary shutdown work approved for 2021 has been largely completed. The decelerator facility has been integrated into the new FAIR control system, the vacuum and RF systems have been checked and the diagnostics are being upgraded to the FAIR standard. A 10-day block of ion deceleration and extraction by the ESR has been dedicated for HITRAP in the upcoming beamtime period.

Highlights in 2021

The work at the cooling Penning trap continues with the help of the TU Darmstadt. To achieve the crucial step of electron-ion interaction and eventually electron cooling, the trapping system has been modified and carefully realigned. The electron source has been refurbished for reliable operation. A local control database and a graphical user interface for the low-energy beamline have been put into operation for the first time, as well as a number of electronic components for manipulating the ions in the trapping system. By means of a dedicated high voltage control and switching system, it is now possible to inject and extract ions at an arbitrary energy of up to 12 keV/q, a feature necessary for the coming beamtime and deceleration of highly charged ions (HCI). Also the vacuum system around the superconducting magnet has seen improvements and the implementation of a baking system, leading to almost an order of magnitude lower residual gas pressure and consequently longer ion storage time.

Along with ongoing efforts for modernization of the local technical systems, the redesigned Penning trap now routinely stores electrons and Highly Charged Ion (HCI) produced by the electron beam ion trap (EBIT) and delivered through the low-energy beamline. This offline part of the HITRAP facility has proven to be so versatile, that even some local experiments were performed. In collaboration with TU Darmstadt, laser spectroscopy of B^{3+} as well as penetration of thin foils with HCI was conducted in order to investigate the feasibility of such experiments with unstable ions at accelerator facilities. Additionally, on-demand extraction and transport of Ar^{13+} ions for a local double-resonance trapping system operated by the GSI atomic physics department (ATP), has also been successfully demonstrated.

Outlook for 2022

In May 2022 a recommissioning period is scheduled with $^{58}Ni^{28+}$ pre-decelerated to an energy of 4 MeV/u by the ESR and extracted towards HITRAP. The main goal is to re-establish the status demonstrated during the last beamtime in 2014, as well as to transport HCI for the first time further down the line, if the deceleration is reproduced with the expected efficiency. In order to meet the main challenge of discriminating between the decelerated and the non-decelerated beams, efforts are ongoing to construct novel, energy-sensitive diagnostic systems, which will enable transport and optimization of extended amounts of HCI at 6 keV/u either to the cooling trap or ideally even behind it. This ambitious goal should provide a proof of concept for experiments with slow, heavy HCI served by the HITRAP decelerator and the cooling trap.

9.1.8 High energy beam transfer lines, status & upgrade

Authors: C. Hessler, O. Geithner, P. Schütt

HEST operation

The high-energy transfer lines (HEST) at GSI have delivered beam to a large number of experiments at different experimental caves during beam time 2021. After commissioning of the ESR-CRYRING@ESR beam line with the new control system during 2019 and 2020, the first user beam time at CRYRING@ESR with beam from ESR via HEST was performed. For this beam time new beam line optics have been experimentally established resulting in a significant improvement of the transmission between the ESR and CRYRING@ESR with respect to 2020. New Faraday cups installed during shutdown 2020 were helpful for beam line setup.

Furthermore, the new beam path to Cave M via FRS has been commissioned with a $^{12}C/^{11}C$ beam. The first experiment at Cave M that was served with beam via this new path was the Biomedical Applications of Radioactive ion Beams experiment (BARB), which used a ^{15}O beam from the FRS.

However, not all experiments served via HEST were running without issues. The HADES test run for the proton beam time planned for 2022 showed e.g. that the beam instrumentation in HEST is not capable to detect low intensity proton beams required for setting up the delicate HADES experiment and that achieving the required focus on the target is challenging.

Preparation for the 2022 HADES proton run

For this reason, several upgrade measures were carried out in order to make the HADES proton run feasible. The procedure for setting up the beam towards HADES is to set up the beam to the first dipole magnet GHADMU1 with normal intensity (~1e9 particles/s), while keeping GHADMU1 and GHADMU2 switched off, so that the beam is dumped in the concrete shielding. The rest of the beam line has then to be set up with low intensity (~1e6 particles/s) to protect the HADES equipment. To make this low intensity beam visible, a new digital camera, which is significantly more sensitive than the previous analogue camera, has been installed at the luminescent screen in the HADES cave. Furthermore, the profile grid in the HADES cave has been upgraded with a new low current readout electronics developed for FAIR [1]. With these upgrades, there are now two independent setups available for measuring transverse beam profile and position in the HADES cave.

To set up the beam onto the target, a precise model of the beam line is required to find the good magnet settings. Investigations after the beam time 2021 showed that the last survey of the positions of the beam line elements in the HADES cave have been done many years ago and that there were hints that the exact positions of some beam line elements have changed in the mean time. Therefore, the information on which the model was based was not reliable anymore and a new survey of the positions of the beam line elements in the HADES cave has been performed by the survey team and linked to measurements in the NE5 area, followed by a re-alignment of the beam line elements. Furthermore, also elements in the beam line which are not measured by the survey team, like e.g. corrector magnets, have been measured with lesser precision using a laser rangefinder. These measurements revealed several discrepancies between the beam line model and the reality, which have then been corrected in the model.

In the last part of the HADES beam line the beam has to overcome a height difference of 70 cm which is realized by two tilted dipole magnets. This results, however, in the coupling of the horizontal and vertical planes making beam steering at the target very difficult. To simplify the beam steering and focusing onto the target, therefore new features have been implemented in the online-model application, called Benno [2], which computes the required magnet strength from the set-values of the beam position/angles at the target and the longitudinal focus position.

HEST upgrades

The HADES beam line has been equipped with beam loss monitors (BLM) in 2018 [3], which have proven to be very useful for localizing beam losses and adapting steering accordingly. Therefore, the upgrade of the HEST beam lines towards caves A and C/D with BLMs has been started in the shutdown 2021.

The beam line towards the ESR is currently equipped with beam position monitors (BPM), however, without readout electronics and cables. Work has started during the shutdown 2021 to put these BPMs back in operation using FAIR-type DAQ modules. Once this upgrade will be completed, this BPM installation can serve as a test bed for developing advanced steering applications which should lead to a reduction of setup time, which will be in particular important for FAIR.

Implementation of HEST devices in sequencer

A sequencer tool has been developed at GSI to automatize testing during commissioning and eventually speed up commissioning. It allows to perform different pre-defined tests on many devices automatically. Most of the HEST equipment is already implemented into the tool: Different magnets, vacuum valves, most of the beam diagnostics. Sequencer creates automatically reports, that include all test errors. The tool will be used in commissioning periods at GSI and FAIR.

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9.2 Shutdown activities

9.2.1 Shutdown activities 2021

Authors: P. Schuett, M. Klich, S. Reimann, M. Vossberg

Time frame and boundary conditions

The 2021 beam time ended on Friday, July 16th. Until July 20th, there were still some final investigations of the running machine. Thus, the core shutdown phase, the period of mechanical work, lasted from July 20th – Nov. 19th. Afterwards three weeks of dry run followed by the mandatory acceptance test of the personnel safety systems by the authorities (§88 – test) were carried out. In the period from Dec. 15th until Jan. 7th, the synchrotron SIS18 was realigned. Recommissioning for the beam time 2022 started as planned on Jan. 10th. Remaining tasks comprise experiment installations and further bake out campaigns in the ESR and experimental installations at CRYRING; all these activities must be finished just before start of the beam time.

Main work packages

The most time-consuming shutdown project was the installation of the WASA experiment in the FRS mid focus, which could be finished just before the start of the beam time 2022.

Another time-consuming and complex task was the installation of GTS1MU1, the 3-way switching magnet towards FAIR, FRS/Dump or target hall. This task needed major dismounting and remounting of shielding walls and roof, and since vacuum was broken, bake out after assembly was mandatory. This task turned out to be the critical path of entire shutdown. First, the concrete shielding barrels had to removed from the target hall; this campaign needed to by synchronized with the construction of a new storage hall south of the main SIS18 target hall. Later on, the usage of the cranes turned out to be a bottleneck: Load cranes were needed at the same time for WASA, the GTS1MU1 shielding measures, roof repair, cabling work and a number of smaller tasks. Several departments needed to cooperate closely to keep the project on time.

At UNILAC, the main focus of shutdown activities was on the improvement of High Current Injector (HSI) operation and the repair of defect components, in particular of water leaks and SEM-profile grids [see separate report on UNILAC shutdown activities]. The UNILAC RF department accomplished refurbishment of the controls for the ALVAREZ A2a+b high power amplifier. Two events during shutdown caused unplanned additional repair efforts: After the transport section UN6 was flooded due to a baffle leak at a dipole magnet, major damages, mainly on beam diagnostic devices, ocurred. Most of the repair was finished in time but a BSM (beam shape monitor) is still awaiting mending from dedicated expert groups. Mid of December, after a five week tunnel closing for commissioning of the refurbished controls of the ALVAREZ 2 RF-amplifiers, a leak between main and fore vacuum at transition of tank shot 2 and 3 had to be fixed. Vacuum conditions were still acceptable, but there was a high risk of deterioration during beam time. Thus, the difficult and sophisticated repair of the vacuum leak started immediately and could be fixed quickly. Thanks to an exceptional effort during weekend evacuation of the recipient started before the Christmas break.

In parallel to the shutdown, FOS High power RF tests were successfully carried out, using the high power RF-amplifier of ALVAREZ tank 4. After the end of testing, the amplifier was successfully reconnected to the tank, and conditioning is scheduled to be launched early in 2022.

At ESR, a Faraday cup on which a vacuum leak has developed during beam time was removed, after that the south arc was baked out. Unfortunately, the Ionization Profile Monitor was damaged during bake out and will not be available during beam time. The removed cup served as a safety device, used to stop the beam, when personnel access to the cave is allowed. Another cup, which was already installed in the ring, was connected to the safety system instead. Later on, several installations for experiments were dismantled and modified by the experiment groups. Final installation in the target section and further bake out will take place in February 2022.

At the beginning of beam time 2022 an impactful experiment is scheduled in the HADES Cave, so this area was explicitly surveyed in September 2021. Incorporation of the results into the beam line model improved the understanding of beam optics significantly. The survey of the remaining accelerator facility took place early in November, alignment was performed toward the end of 2021 and beginning of 2022. The alignment activities were affected by the repair at the UNILAC tanks, but was nevertheless successfully completed just in time thanks to excellent support from the different departments.

Several experimental installations were conducted in the CRYRING during shutdown. The experiment components had to be installed, adjusted and finally baked out. Media supply lines were installed and supporting structures were set up. In the beam time 2022, the HITRAP experimental area will be put back into operation first after a long time. For this purpose among other things the vacuum interlocks along the beamline were checked, the coupling loop of the IH was replaced and beam diagnostic components were reconditioned.

Infrastructure shutdown and civil construction

Major maintenance work on medium voltage switchgears, which involve several weeks of electricity shutdown, were shifted to the shutdown 2022/23. Nevertheless, electricity cuts were necessary for urgent repair: Medium voltage switchgear =AC was shut down for three days in September. Meanwhile major parts of GSI were without power supply. In the week before, alternate power supply was provided for the most critical technical installations (biology, vacuum, etc.).

The switchgears =EH and =EJ provide for power supply of the UNILAC-Experimental Hall and the container C09. They were shut down for one week each. However, the tests at the FOS could be continued without any issues, as they received an alternative power supply.

A large ongoing project is the renovation of the roofs of nearly all buildings on campus. During shutdown 2022 the roof renovation for the main control room (HKR) was accomplished as well as for the halls TH and EX. The latter was synchronized closely with the main tasks of the accelerator shutdown.

9.2.2 UNILAC shutdown activities 2021

Authors: U. Scheeler, H. Vormann, W. Barth, M. Vossberg

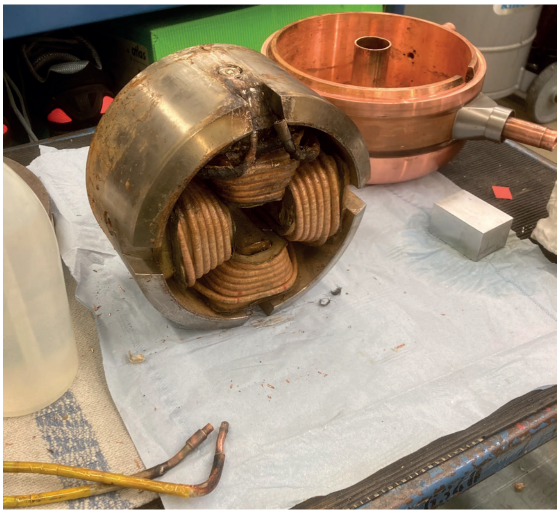


Figure 67. ALVAREZ-drift tube spare part: Body, magnet and damaged conductors.

The main focus of shutdown activities was on the improvement of High Current Injector (HSI) operation and the repair of defect components, in particular of water leaks and profile grids. During the 2021 beam time, water leaks occurred at the quadrupole triplet in front of the Low Energy Beam Transport behind the High current ion source, at the magnet coil of the steerer US4MS5H, at a steerer mounted inside the end plate of ALVAREZ 3, and at a water cooled baffle plate in the magnet chamber of UXCMU3. The upper magnet yoke and the chamber were dismantled, a new baffle plate has been manufactured and installed. The drift tube no. 10 of ALVAREZ 1 cavity was replaced due to water leakage. The fabrication of the spare part started right after its breakdown (April 2021). In August all subcomponents were available and the assembly of the drift tube started. During the electronic welding of the two end plates with the drift tube body, the supply pipe of the coils was damaged. One end plate has to be removed and the magnet was again replaced. A new end plate had to be manufactured; repair and welding are still ongoing. Just at the beginning of the shutdown phase, a vacuum leak has been observed in the High Charge State Injector section. Due to parallel maintenance at the vacuum control system, it could be detected only after one week - the beam line UN6 was filled with cooling water and many installations have been damaged. This event caused significant repair efforts; bunch structure monitor repair is still ongoing.

Water leaks of beam line insertions are very disturbing as during shut down periods their detection is very difficult. It often occurs, when the pressure of the cooling system changes. A global switching-off of the cooling circuits is no solution, as the corrosion in the pipes increases, sediment load falls out, and bottlenecks got blocked. We tried to keep the different beam lines under vacuum and permanently surveyed the vacuum pressure. At the HSI RFQ structure, several issues had to be managed. A slightly bigger fixed plunger was installed in order to adapt the switch-on position to the frequency range of operation. The electric motor of the moveable plunger has been exchanged twice; the second attempt has been performed successfully with a new and modified motor type. At super lens, the RF antenna was exchanged succeeding an improved RF coupling and reduced reversed power. About 12 profile grids with broken wires have been dismantled and repaired step by step. There were grids with more than 20 defective wires. The reason for the massive demolition is not clear so far. In any case, the beam loss detection and the grid protection system, which limits the allowed beam loss, needs to be checked and modified in the future. In November, the commissioning of the new control of the ALVAREZ 2 amplifiers was associated with a five-week tunnel closing. Afterward, a leak between the main and fore vacuum has been detected at ALVAREZ 2A between cavity sections 2 and 3. Due to expected long and difficult repairing, the required exchange of the gold sealing was carried out still in the last week before the winter break. Vacuum commissioning could take place before the new year.

9.2.3 Progress of the RF system modernisation at the ALAVEZ section of the UNILAC

Authors: B. Schlitt, G. Schreiber

Figure 68. New control cabinet (leftmost) and high-power RF amplifier (HPA) of the ALVAREZ tank A2a after refurbishment (left photo). Backside of one of the new control cabinets (centre) and mounting panel with PLC sub-unit and further electrical equipment at the A1 HPA (right).

To improve the operational reliability of the 108 MHz RF systems at the ALVAREZ section of the UNILAC and to prepare the systems for further upgrades, a substantial modernisation programme was launched in 2014 comprising various different tasks [B. Schlitt et al., GSI Scientific Report 2014, p. 413]. Among them, a state-of-the-art system based on Programmable Logic Controllers (PLC) for control of the five 1.7 MW high-power RF amplifiers (HPA) was developed in the Linac RF department to replace the old relay-based controls. A prototype PLC system was installed and tested extensively at the ALVAREZ tank A3 HPA in previous years [B. Schlitt et al., GSI Scientific Report 2016, p. 392]. A comparable PLC system was installed at the new 1.8 MW Thales HPA [B. Schlitt et al., GSI-FAIR Scientific Report 2017, p. 353] feeding the A4 tank. Since 2018 and 2019, respectively, these upgraded systems at A3 & A4 were successfully operated during regular beam times. In parallel to routine operation of these prototypes, the system design of the new HPA control was further optimised. Based on this improved design, the A1 HPA was refurbished during the GSI accelerator shutdown in 2020, and the A2a and A2b HPAs in the shutdown 2021 (Figure 68). Thus, an important milestone was reached in 2021: All HPA at the ALVAREZ linac and the corresponding 1 MVA anode and screen grid power supplies have been refurbished and are now operated by the new PLC systems.

A novel control cabinet was set up at each HPA (Figure 68). Besides the central part of the new PLC system (including a touchscreen HMI), it comprises a new fast measurement and interlock system for monitoring of all operation parameters, fast interlock generation, RF pulse termination, and for signal preparation. A rack-mount oscilloscope and a set of analogue instruments are used for signal measurements and visualisation. Furthermore, a new microcontroller-based electronics for resonant frequency control of the accelerator cavity and a new commercial control grid power supply were installed in each control cabinet.

The complete electrical HPA control equipment and the cabling of the HPA were renewed. The new electrical equipment was mainly mounted on two mounting panels: One of them installed in the HPA (Figure 68, left and right: central part of the HPA, illuminated) comprising also a sub-unit of the new PLC, and the other mounting panel at the backside of the new control cabinet (Figure 68, centre). This allows direct access to all components during routine operation as well as for troubleshooting and maintenance.

The refurbished A1 HPA was operated successfully already during beam time in 2021. The renewed A2a and A2b HPA were re-commissioned and tested during a test block in Q4/2021 and are in regular operation for the beam time 2022 by now. In the accelerator shutdown 2022/23 the update of the prototype HPA control at the A3 system to the same optimised standard as installed at A1 and A2 is planned.

Furthermore, the EMC shielding of the new Thales amplifier was improved by the manufacturer in 2021. The electromagnetic radiation emitted to the environment was reduced and was checked by EMC measurements afterwards. The procurement of a second Thales HPA including some design optimisation is planned from 2023 on.

9.2.4 Operation infrastructure support

Authors: T. Dettinger, K. Dermati, M. Henke, J. Holluba, M. Romig, S. Teich, G. Walter

In 2021 different support activities have been carried out by the Operation Infrastructure Support OIS, i.e. the departments Technology Laboratory and Mechanics & Metalworking. Both departments continued their strong collaborations e.g. of using special manufacturing, welding, and galvanic Copper plating technologies. Special examples for these ongoing activities are construction of different parts and devices for the FAIR accelerators (e.g. p-linac, SIS100, etc.) including the ALVAREZ replacement of the UNILAC. In addition, a variety of experimental setups have been supported during FAIR Phase-0 beam time 2021 and in preparation of the beam time 2022.

Support service

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

- Production of a sparse drift tube for the existing UNILAC ALVAREZ, a challenging activity as the "old-fashioned" manufacturing technology using solid Cu material was done for the first time at GSI after decades because no spare parts were available
- A further highlight was the production of two complicated pocket drives for the fragment separator.
- Production of electrodes for the UNILAC super lens, mounting will follow in 2022.
- Ongoing series of cutting and welding of flanges for prototype of SIS100 magnetic dipole vacuum chambers
- Successful copper plating of the new ALVAREZ FOS tank interconnection rings and endplates
- Copper plating of the p-linac CCH 1 demo cavity has shown a inhomogeneous copper distribution due to the complicated geometry of the structure. Simulations of the resulting field geometry have been performed by a group from JWGU Frankfurt. Different measures (e.g. geometrical adjustments mechanical construction of structure and anode) are still under discussion.
- FEM analysis support for SIS100 Quadrupole Beam chamber, TPC active target, PHELIX, HEBT as well as EZR Ion Source.

In parallel to the technical support of the different projects the Galvanic retrofitting has made significant progress. The building and operation permission have been given by the local authorities, and the final planning phase is now ongoing. Tendering procedures of construction work for the different technical subsections have been performed.

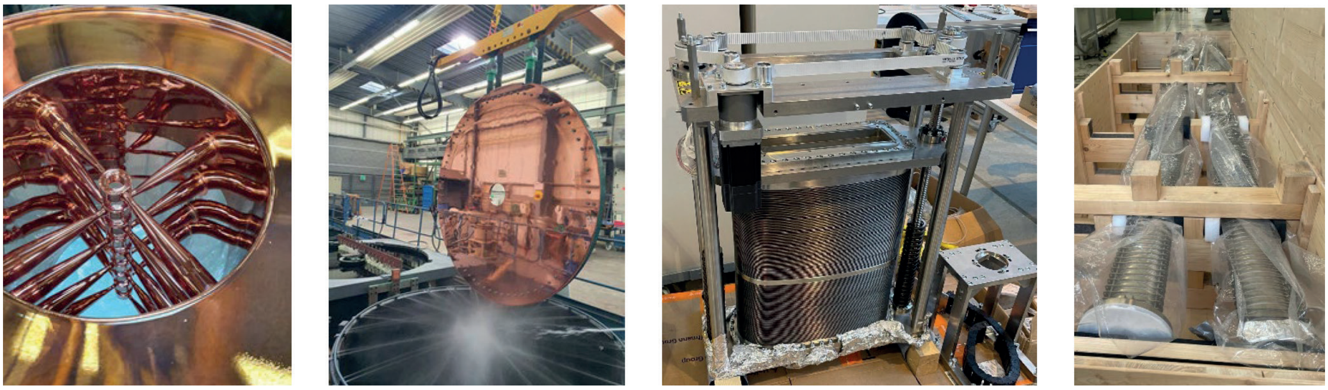


Figure 69. Left to right side: a) Copper plated demo CCH1 structure of the p-linac. b.) Copper plated ALVAREZ FOS end plate. c.) Pocket drive for FRS, d.) Two dipole series vacuum chambers of SIS100.

9.3 Accelerator R&D

9.3.1 UNILAC machine investigations

Authors: W. Barth, U. Scheeler, H. Vormann, M. Miski-Oglu, M. Vossberg, S. Yaramyshev

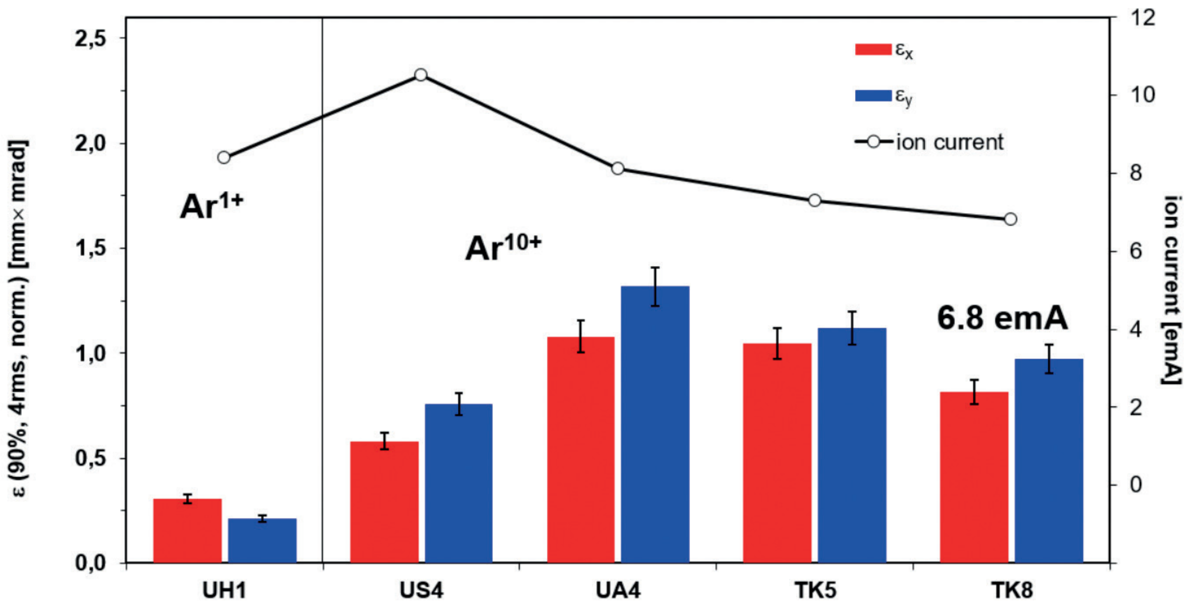


Figure 70. High intensity ^{40}Ar-beam emittance (4 x rms, 90%, normalized) and current measurements along UNILAC and TK.

The measured High Current Injector (HSI) intensity level behind the gas stripper for medium heavy ions beams ($^{40}Ar^{10+}$) exceeds the value of 7 emA specified to fill the SIS18 up to its space charge limit; this enables to investigate space charge dominated beam transport inside the entire UNILAC and the transfer line to the SIS18. This means that the beam transport behaviour is mainly determined by the intrinsic field of the beam bunches. For further high intensity measurements, the stripper gas density was chosen such that the desired Ar^{10+} current of 7 emA was achieved after optimization of the poststripper (ALVAREZ drift tube linac) and TK. For argon high-current operation the effect of emittance asymmetry (driven by a target scattering dependent on the transverse unequal beam width) observed for heavy ion beams, such as behind UNILAC gas stripper target at 1.4 MeV/u, turns out to be much smaller. This is justified by the fact that the horizontal beam spot can be set much larger due to the extremely high space charge forces, since the requirements on the beam spot size for the separation of the neighbouring argon charge states are much smaller. For the argon high-current experiments, the RF-supply of ALVAREZ tank 4 was not available, hence the UNILAC energy was 8.6 MeV/u. An $Ar10^+$-transmission of 65% for poststripper and transfer channel could be achieved for this high intensity. Bearing in mind the very high ion current in these UNILAC sections, the average transverse rms-emittance growth is relatively low at 35% and fits perfectly into the transversal acceptance of SIS18. The evolution of the transverse beam emittance along the UNILAC and transfer channel under high current conditions is displayed in Figure 70. High current front-to-end-simulations at GSI-UNILAC were published in [1]. The simulated emittance growth depends strongly on the starting conditions. For high current beam operation the emittance grows under ideal conditions inside poststripper and TK sections by almost a factor of 2 at a beam transmission of 70%.

The measured beam brilliance is defined as the measured beam current divided by the accordingly measured beam emittance. The fractional brilliance is obtained when the measured beam emittance is cut in the post analysis so that particles (with highest momentum) are removed from the limiting edge. The remaining phase space area (divided by the remaining current) results in the corresponding fractional brilliance. For brilliance analysis at the end of the transfer channel (TK8), the fractional emittance values were determined in the horizontal and vertical directions, resulting in corresponding fractional brilliance quantities, which can be obtained by cutting the phase space in the dedicated collimation channel directly in front of the installed emittance measurement device.

The analysis of the measured high-current (fractional) brilliance as a function of the associated measured beam current shows, that the brilliance increases from the edge to the core of the phase space distribution. By suitable collimation of the phase space distribution such that 4 emA Ar^{10+} remains, the SIS18 space charge limit can be reached, since this ion current is located in a much smaller phase space area. By this method, the FAIR design condition in particular for medium heavy ions could be fulfilled.

References

- [1] W. Barth, et al., High current beam dynamics for the upgraded UNILAC, Particle Acc. Conference, Vancouver p 1897-1899 (1997)

9.3.2 Report on the UNILAC pulsed stripper

Authors: P. Gerhard, M. Maier

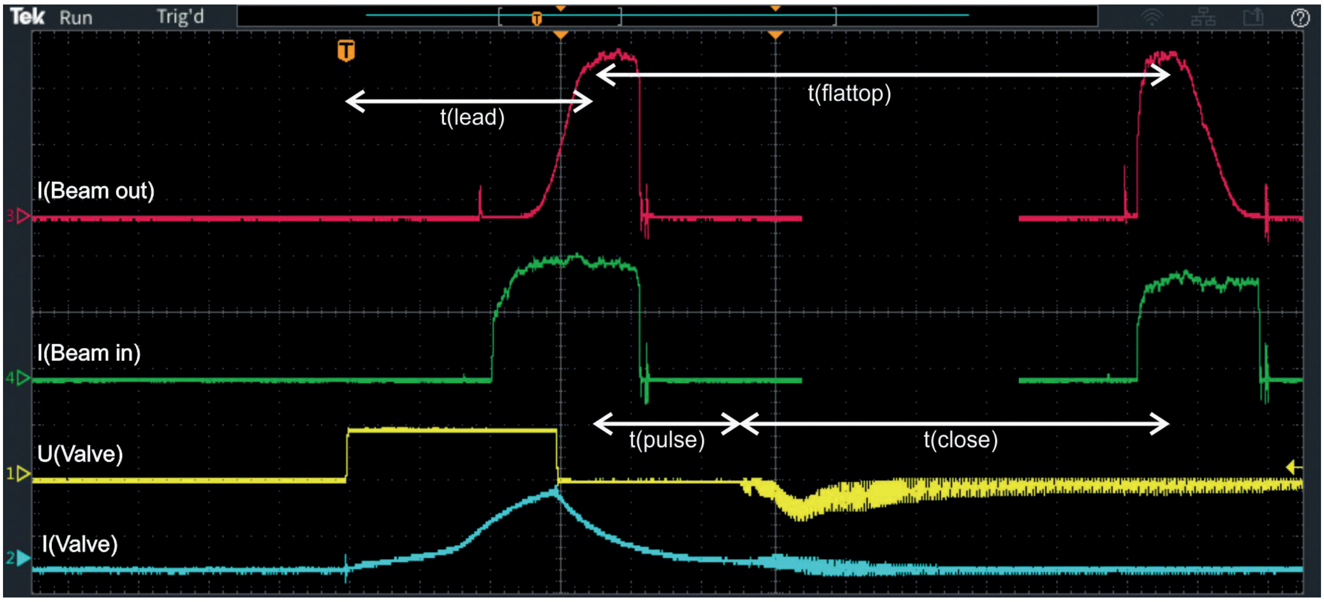


Figure 71. Hydrogen gas target buildup and depletion measured with a uranium beam, shown as composition of two oscilloscope readouts. Beam current before (I(Beam in), green traces) and after stripping (I(Beam out), red traces) is shown together with the voltage (U(Valve), yellow trace) and current (I(Valve), cyan trace) applied to the valve coil. White arrows indicate the lead time from start of energising the valve until the gas target has built up, the intended pulse duration, the time it takes the valve to close after end of energising, and the total flattop time available. The end of the flat top was measured with a second, delayed ion beam pulse (red and green traces on the right).

High intensity heavy ion beams are a main constituent of the FAIR research programme. They will be provided by the UNILAC via the high current injector HSI. Generated in high current sources, these ions originally have low charge states. To allow for efficient acceleration in the UNILAC and SIS18, a gas stripper is located at the end of the HSI to reduce the mass-to-charge ratio below 8.5. An effort has been made to enhance the stripping by introducing hydrogen instead of nitrogen as stripping target, thereby increasing the stripping efficiency by up to 60% [1]. The main focus of the project is now on transforming the experimental setup into a system suitable for regular operation.

In 2021 the draft technical and safety concept has been reworked following a safety advisory opinion given in 2020. Changes and additions to the safety measures have been included, and the implementation of these safety measures as well as other parts of the technical implementation have been detailed. This also caused minor changes of the overall system design. Discrepancies between some of the drafted technical implementations and the advisory opinion were encountered, mainly related to the pressure monitoring in the gas stripper chamber. Alternatives have been developed and are proposed. The revised and substantially extended version of the technical and safety concept for the pulsed hydrogen gas stripper is ready for final risk assessment.

Preparative infrastructure for the pulsed gas stripper was installed. A large safety cabinet, which will house the hydrogen gas supply, was put into place at the technical supply area next to the UNILAC tunnel. In support of this, an explosion safe ventilation was installed. The ventilation duct had to be routed outside the building through the crowded UNILAC RF gallery. To feed the fast pulsed gas valves in the gas stripper, high pressure gas pipes and shielded power cables were laid from the technical supply area into the UNILAC tunnel. In order to separate the gas pipes from hazardous electric cabling, a long and intricate route had to be established, crossing two radiation protection walls.

Work on the test stand focused on the preparation of safety tests of the pulsed valves. The valve controller and its control software were upgraded in order to enable direct temperature measurements of the magnetic coil of the valves. It took considerable effort to turn this essential feature operational. Additionally, full control of the valve opening directly by the accelerator timing was enabled by a firmware upgrade of the valve controller. This allows for a more flexible, unattended operation during test beam times and is a major step towards routine operation.

As in previous years, the experimental setup was operated during a machine beam time. New diagnostic and auxiliary equipment was employed for the first time. This proved to simplify the setup, operation and conduction of tests substantially. In order to make use of the full valve control by the accelerator timing, a programmable gate pulse generator was installed and connected to the timing domain of the gas stripper. A basic operating programme was developed to allow for simple programming and control of the generator. Apart from providing three days of hydrogen operation for UNILAC and SIS18 machine experiments, gas stripper related investigations were conducted. Objectives were reducing the total gas load by varying the valve control, and specifying routine operation parameter ranges for the valves for further safety testing. The experiments covered time and pressure dependence of the gas flow for hydrogen in comparison to nitrogen, opening and closing characteristics of the fast valves, and build up and depletion of the gas target. Measurements of electrical and gas parameters together with observation of the stripping efficiency using a uranium beam were combined. An example of the measurements is shown in Figure 71. The results will be further analysed by complementary measurements on the test stand, i. a. using a microphone to observe the valve operation mechanically.

References

- [1] Gerhard, P.; et al. Development of Pulsed Gas Strippers for Intense Beams of Heavy and Intermediate Mass Ions. Proc. LINAC'18, Beijing, China, Sep. 2018, pp. 982-987. DOI:10.18429/JACoW-LINAC2018-FR1A05

9.3.3 Progress on design and construction of the new post-Stripper section of the UNILAC–ALVAREZ 2.0

Authors: S. Mickat, X. Du, L. Groening, M. Heilmann, M. Kaiser, A. Rubin, C. Xiao

The ALVAREZ 2.0 DTL will replace the existing post-stripper DTL of the GSI UNILAC [Mickat, S. et al.: Progress on the ALVAREZ 2.0 DTL post-stripper section of the UNILAC, GSI Report (2020)]. The main activities in 2021 can be itemised as follows in brief.

Preparation and performing high power RF tests with the FOS cavity

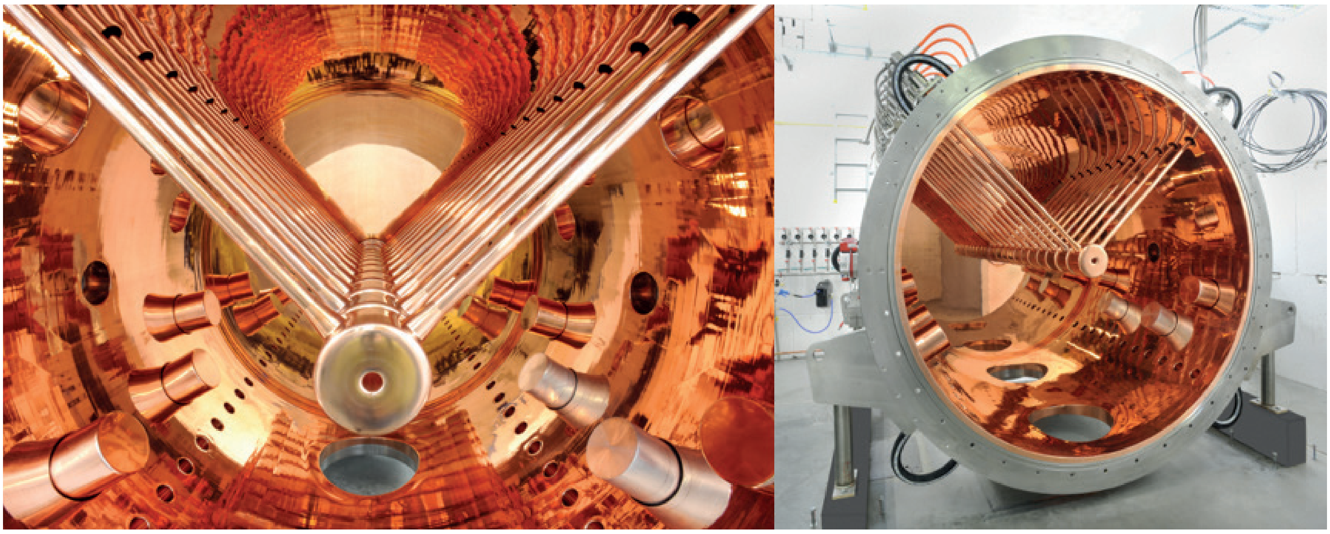


Figure 72. View into the FOS cavity at the prepared RF test stand (photo: G. Otto, GSI, 2021).

In May 2021 the 1.8 MW RF-system of the existing post stripper DTL was disconnected to serve as RF-source for the FOS cavity. Since the FOS test stand was ready for operation in time, RF conditioning starts in July 2021 [Schlitt, B. et al., this report]. In September 2021 the cavity was powered with up to 400 kW at flat top duration of 1.4 ms and repetition rate of 10 Hz with reflections as low as few percent, which is beyond the nominal RF-parameters for FAIR at 286 kW, 1.0 ms flat top of the RF pulse at 3 Hz repetition rate (Figure 72).

Preparation and tendering of the large DTL components for series

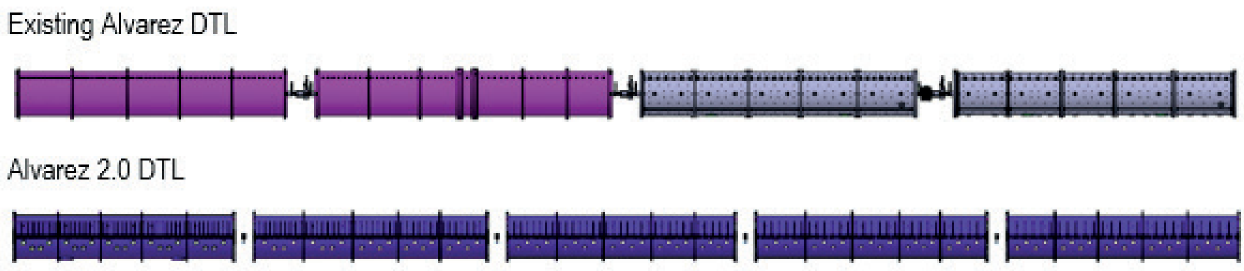


Figure 73. Existing ALVAREZ DTL in comparison with the ALVAREZ 2.0 DTL design.

In parallel to the high power RF tests with the FOS cavity the large components for series, 25 tank sections and 10 end plates, were tendered. For the tender documents the DTL design was iterated, reviewed, and agreed finally: five cavities of ALVAREZ-type, nearly of same length, are connected by four standardised inter-tank sections (Figure 73). In October 2021 negotiations with three bidders were conducted. The order shall be placed early in 2022.

Prototyping: drift tube and magnet power supply

The first industrially produced drift tube with an integrated quadrupole was delivered in July 2021. At site the field parameters of the quadrupole were measured very well within the specified tolerances. A complaint was made that the electrical leads were not fixed adequately for pulsed operation. With minor effort the manufacturer was able to rectify this issue significantly. With respect to the series this issue is assumed to be manageable now. To operate the integrated quadrupoles suitable electrical power supplies were designed in-house. Two power supplies as first of series were ordered in July 2021 and delivered in December 2021 (Figure 74).

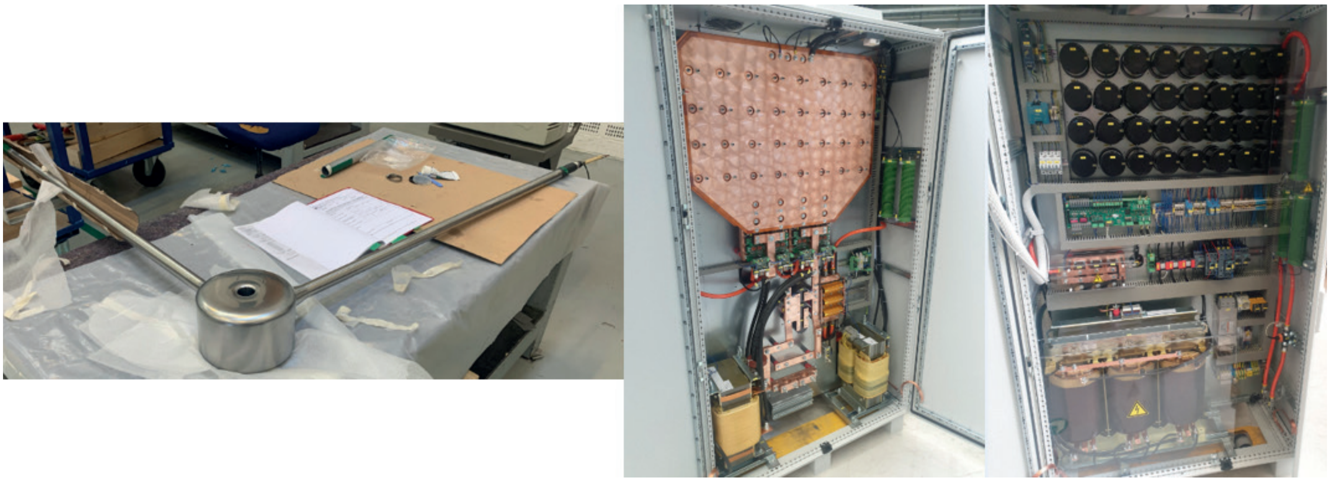


Figure 74. Left: drift tube prototype before delivery (M.N. Pederson, Danfysik, 2021). Middle and Right: view into the rack for magnet power supply prototype (M. Heilmann, GSI, 2022).

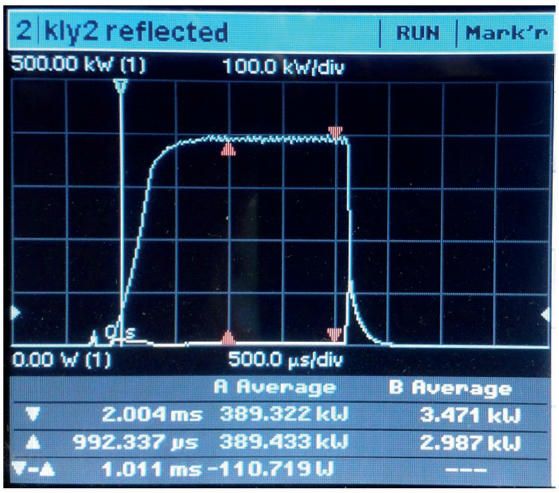
9.3.4 High-power RF tests of the ALVAREZ 2.0 FOS cavity

Authors: B. Schlitt, C. Herr, M. Hörr, G. Schreiber

From July to December 2021 a comprehensive programme for RF commissioning and high-power RF testing of the ALVAREZ 2.0 [S. Mickat et al., this report] FOS cavity was performed in close cooperation of the LINAC RF and the UNILAC Post Stripper Upgrade (PSU) departments. Lead by the PSU department, an RF test bunker was prepared at the former experimental station Z7 in the GSI experimental hall (EH) in previous years [S. Mickat et al., GSI-FAIR Scientific Report 2019, p. 147]. An 80 m long 6 1/8" coaxial transmission line was installed from the UNILAC RF gallery to the test bunker by an external company as well as a set of cables for RF pick-up signals, interlock (FOS cavity water cooling) & vacuum signals, and for control of the motorized plunger actuators. The bunker access doors were integrated into the existing radiation protection interlock system at the UNILAC.

The new 1.8 MW high-power RF amplifier from Thales [B. Schlitt et al., GSI-FAIR Scientific Report 2017, p. 353] was used for the tests. Prior to connection of the amplifier to the FOS cavity, various low-level RF measurements were performed to adjust the matching of the RF coupling loop and to check the cavity mode spectrum and tuner range, etc. The RF line length was checked by RF measurements to avoid an interference of the operation mode at 108.4 MHz with RF line resonances.

RF conditioning started mid of July 2021. After stepwise conditioning starting with shorter RF pulses at low power, power levels exceeding the design value of ~290 kW at 2 ms pulse length were reached in open-loop operation after about two weeks. Closed-loop operation to control the RF field amplitude and phase in the cavity and automatic tuner control to keep the resonance frequency of the cavity during RF operation were established. The FOS was operated routinely on weekdays from August to October at typical RF pulse powers around 300 to 400 kW and beyond and at design pulse parameters (10 Hz pulse repetition rate at 2 ms pulse length, see Figure 75, left part). All operation parameters of the amplifier as well as forward and reverse RF power and the vacuum pressure in the cavity were continuously monitored for interlock generation, for RF pulse termination in case of arcing or failures, and for signal measurements.



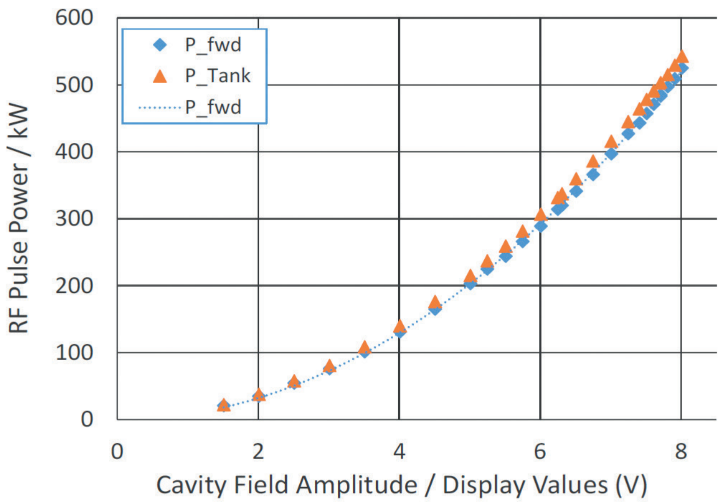


Figure 75. Left: Example of an RF pulse power measurement of forward (upper trace, Channel A) and reverse (lower trace, Channel B) RF power at the amplifier output during closed-loop operation. Right: Measured RF pulse powers vs. field amplitude in the cavity.

All RF power measurements were carefully calibrated considering all cable losses, coupling factors, etc. Figure 75 (right part) shows the forward RF power (diamond symbols) measured with a power meter at a directional coupler in the RF output line of the amplifier vs. the RF field amplitude measured at a pick-up at the FOS cavity. The dotted line is a second order polynomial fit which matches well the measured forward power up to the highest values beyond 500 kW. The triangle symbols in Figure 75 show the RF power measured at a second calibrated pick-up installed at the cavity, being a direct measure for the field energy stored in the cavity. They agree well with the forward RF power within about 5 % showing the high accuracy of the different power measurements. The ratio of stored energy and forward RF power is almost constant up to the highest field levels. Thus, practically all the forward power is converted into field energy and nearly no dark currents occur even at RF powers almost twice as much the design value.

X-ray spectra of the bremsstrahlung emitted by secondary electrons accelerated in the gaps of the ALVAREZ structure were recorded in cooperation of the PSU department with the safety and radiation protection (SRP) department at GSI at different RF powers in order to verify the gap voltage. The measurements confirmed that the design voltage required for acceleration of U^{28+} ions was reached at around 290 kW as expected from field simulations.

In November & December continuous run tests in 24/7 operation mode were performed in blocks up to a duration of eleven days. Various operation modes at low and high powers and mixed operation schemes changing the pulse power setting from pulse to pulse in a defined sequence similar to real operation modes at the UNILAC were successfully tested. Stable routine operation without any breakdowns was demonstrated within and also exceeding the design power range.

Besides operation at design levels, reliable operation at up to 40 % higher pulse power (~400 kW) at 2 ms, 10 Hz pulses as well as at 50 % longer pulse length (~3 ms) at pulse powers around 300 kW were major objectives of the tests in order to verify safety margins to electric field breakdown limits, aging, and other degrading effects. All these power settings were successfully tested in daily operation as well as during the continuous 24/7 testing blocks. Breakdowns occurred occasionally just at the highest powers.

Overall, stable and reliable RF operation could be demonstrated successfully over a wide range of operation modes and pulse powers and the general design of the FOS could be confirmed. Finally, the campaign ended mid-December 2021 and the Thales RF amplifier was reconnected to the ALVAREZ A4 tank at the UNILAC for operation during beam time 2022.

The fruitful cooperation with our colleagues from PSU and SRP departments is greatly acknowledged by the authors.

9.3.5 Magnet system design for the 18 GHz ECRIS upgrade

Authors: F. Maimone, A. Andreev, R. Lang, J. Mäder, P. Patchakui, K. Tinschert, R. Hollinger

A new room-temperature ECR Ion Source (ECRIS) is currently under development [1]. The Heavy-Ion Ion Source Injector (HIISI [2]) developed at the Department of Physics, University of Jyväskylä (JYFL) is used as a prototype for the new ECRIS within the framework of a cooperation agreement between the JYFL and GSI. In order to increase the ion beam intensities, the new ECRIS will operate at a higher frequency (18 GHz) than the existing 14.5 GHz CAPRICE ECRIS installed at the High Charge Injector (HLI). Under the semi-empirical ECRIS scaling laws, a simultaneous increase of the confining magnetic fields is necessary to make effective use of the higher plasma density.

The minimum-B magnetic field structure for plasma confinement is created by the superposition of radial and longitudinal magnetic fields. The axial magnetic field is produced by three normal conducting coils. The radial plasma confinement is provided by a permanent magnet hexapole, which has a Halbach structure with 36 segments. Extensive study has been carried out to maximize the radial confining field provided by the hexapole assembly and minimize the risk of demagnetization of permanent magnets [3].

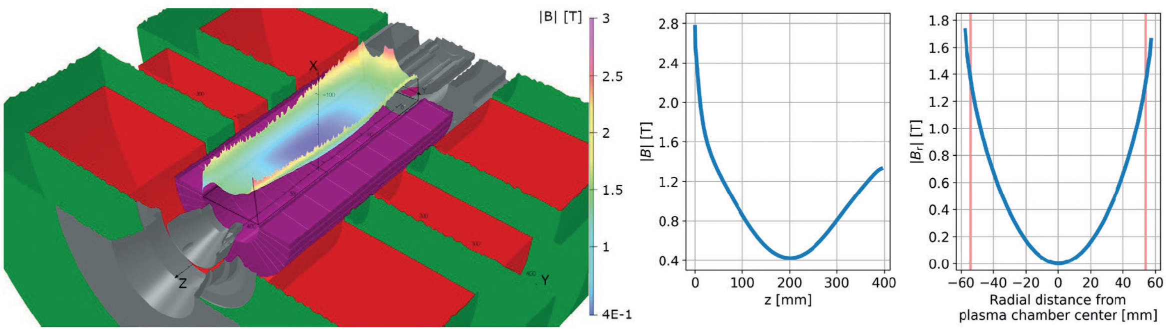


Figure 76. Minimum-B magnetic field structure (left), axial magnetic field (center), and radial magnetic field (right).

Computer simulations of the complete magnetic system have been carried out with the Opera software package [4]. The three-dimensional view of the magnetic field structure is shown in (Figure 76) left). The maximum axial magnetic fields at the injection and extraction ends of the source plasma chamber are about 2.8 T and 1.3 T, respectively (see Figure 76) in the middle). The minimum magnetic field at the center can be adjusted by varying the current in the middle coil. The radial field profile in the middle of the hexapole assembly is depicted in (Figure 76) (right). The application of innovative technical solutions adopted from the HIISI allows to reach the maximum radial magnetic field of 1.35 T at the wall of the plasma chamber (see red shaded areas in the right Figure 76). Therefore, the study confirmed that the desired magnetic field configuration can be achieved with the proposed magnet system design.

Another challenging aspect of the hexapole design that requires a careful investigation is the risk of partial demagnetization of the permanent magnets. Therefore, a demagnetization analysis has been carried out to investigate this effect. The analysis showed, that a small fraction of the permanent magnet material, which corresponds to 2% of the total permanent magnet volume, is subjected to demagnetization at room temperatures. These regions are located at the outer radius of the hexapole assembly. Therefore, a refrigeration system will be used to cool down the hexapole assembly in order to avoid demagnetization of the permanent magnets by increasing the coercivity of the magnet material. The specifications of the refrigerated hexapole chamber will be finalized by considering the results of dedicated thermal and stress analyses.

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9.3.6 Status report advanced demonstrator testing

Authors: M. Miski-Oglu, W. Barth, M. Basten, C. Burandt, F. Dziuba, V. Gettmann, T. Kürzeder, S. Lauber, J. List, S. Yaramyshev

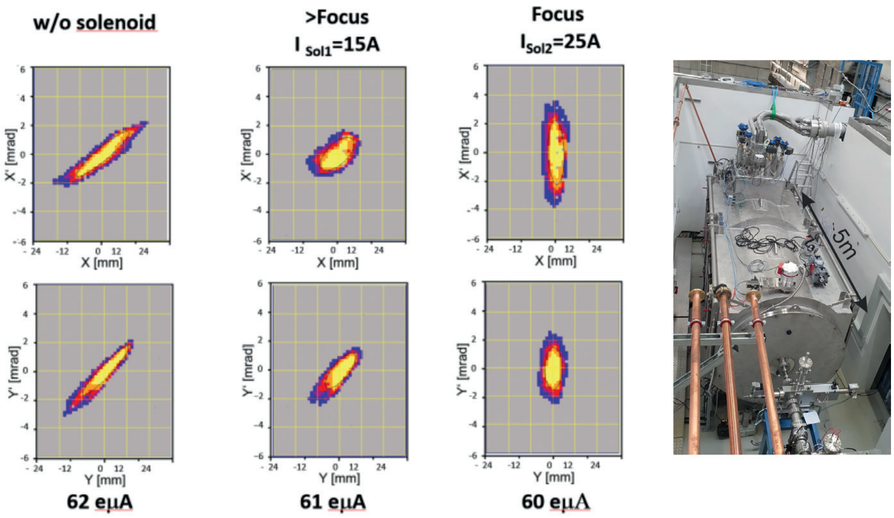

Figure 77. Measured transverse emittances of an Ar^{8+} beam w/o SC solenoids, with excited solenoid 1 and solenoid 2 (left); the photograph (right) shows the installed cryostat during test beam time 2021.

In 2020, the design of the cryogenic module prototype (Advanced Demonstrator) has been finished. This standard module will be equipped with three superconducting (SC) Cross bar H-mode (CH) acceleration cavities CH0-CH2 and a SC rebuncher cavity, as well as two SC solenoids. For stable 4K operation of the entire cw-Linac HELIAC (HElmholtz LInear ACcelerator) a cryo plant with 240W total cooling power@4K is required. The cryo plant of the GSI-Series Test Facility (STF) has a cooling capacity of 700W and is already in operation for testing of SC SIS100 dipole magnets. After magnet testing is finished, the cryo plant is foreseen to supply the HELIAC and the testing area in the "GSI-Stripperhalle" SH1/SH4. The helium supply infrastructure is in operation since 2020. In preparation for further beam test activities, the beamline, which connects the High Charge State Injector (HLI) with the testing area, was installed. The beamline comprises a pair of phase probes for Time Of Flight (TOF) measurement of the incoming beam energy, quadrupole lenses and a 4-gap RF-buncher cavity. The cryostat equipped with SC solenoids and CH-cavity-dummies has been delivered to GSI in June 2021. (Figure 77 right) shows the installed cryostat within the radiation protection shelter. The beam diagnostics bench behind the cryostat is equipped with phase probe pairs, a slit-grid device, a bunch shape monitor (Feshenko monitor) for measurements of the longitudinal beam profile. This setup allows complete 6d characterization of the ion beam - in 2021 two test beam times were successfully accomplished. During the first beam time in May two Feshenko monitors were commissioned, one for HELIAC and the other monitor for FAIR p-Linac. The measured longitudinal profiles for different rf-amplitudes of two bunchers are used for the reconstruction of the 2d longitudinal distribution at the exit of HLI. The projection of the reconstructed distribution shows excellent agreement with measurements of the third Feshenko monitor installed at the exit of HLI. Furthermore, the longitudinal profile was measured with a novel fast Faraday cup. The agreement with the Feschenko monitor measurement is excellent as well. The second beam time in June was dedicated to the commissioning of the cryostat and the SC solenoids. One of the key criteria for site acceptance test of the cryostat is the fidelity of transversal positioning with respect to the beam axis of the accelerator components during evacuation of the isolation vacuum and during the cool down phase. Prior beam test the position of temporarily installed cross hair targets - fixed on entrance and exit of both solenoids – could be measured during evacuation and cool down with a dedicated telescope equipped with a CMOS camera. The analysis shows a movement in transversal plane smaller than 0.1mm, which is within the scope of the cryostat specification. After the removal of the target, the cryostat has been integrated into the beam line and could be cooled down again. The electrical functionality of both solenoids and their current leads were proved by ramping up to the maximal design current of 100A. The beam was successfully focused on the profile grid behind the set up. Under the influence of the solenoids, the beam was only slightly displaced. It was easily possible to compensate the offset by gentle excitation of the steering coils, integrated in the solenoids. Figure 77 shows the measured emittance of an Ar^{8+} beam behind the cryostat without and with subsequently excited solenoids. The measured emittance growth is negligible, so that functionality of the solenoids is fully validated. Altogether, the infrastructure and the individual accelerator components are ready for the beam test of the cryogenic module in June 2022, which is a major milestone for the entire HELIAC-project.

9.3.7 HElmholtz LInear ACcelerator R&D activities

Authors: F. Dziuba, W. Barth, M. Basten, C. Burandt, V. Gettman, T. Kürzeder, S. Lauber, J. List, M. Miski-Oglu, S. Yaramyshev

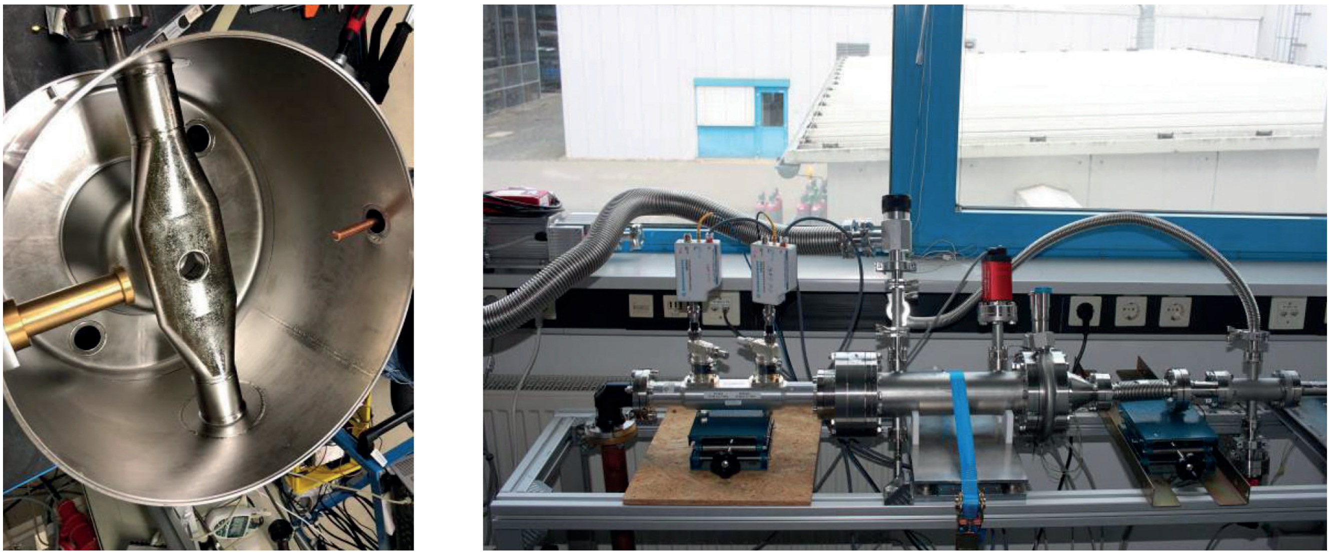

Figure 78. Superconducting single spoke buncher cavity during manufacturing (left) and power coupler test setup (right).

For longitudinal beam matching each cryomodule (CM) of the HELIAC (Helmholtz Linear Accelerator), which is currently under construction at GSI, is equipped with a superconducting 217 MHz single spoke buncher cavity (see Figure 78 left). The production of the first two buncher cavities, designed for a particle velocity of $\beta = 0.07$ for CM1 and CM2, already started in 2020. Within 2021, the welding work on the cavities was successfully completed. In this phase, all production steps were carried out on the basis of detailed RF (radio frequency) and structural-mechanical simulations in cooperation with the manufacturer in order to achieve the target frequency of the cavities. In December 2021, the cavities were ready for the final surface preparation, which includes several chemical etching steps, a 650 °C bakeout for 24 hours, and high-pressure rinsing with ultrapure water. The surface treatment is scheduled for completion in early 2022. So far, all frequency-influencing effects during the manufacturing process, such as welding shrinkage, pressure sensitivity and thermal shrinkage, have been successfully verified with corresponding simulations. It is planned, that both cavities will be delivered to GSI in February 2022 for first performance tests with low-level RF power at 4 K. In the next step a full performance test with beam of the completely equipped CM1 is planned for June 2022. In order to bring the power couplers for the superconducting RF cavities of the HELIAC to series production stage, a number of tests were carried out. In a high power test (see Figure 78 right), the performance of the coupler was confirmed for up to 5 kW of forwarded RF-power in CW (continuous wave) mode. During the test different operating and conditioning procedures were developed and tested. After successful completion of the RF tests, the coupler was integrated into the first HELIAC-cryomodule CM1 and subjected to further tests. In this context, the static heat load and the temperature gradient of the coupler was determined. Furthermore, the dynamic heat load applied to the cryo-system, caused by ohmic losses of the power coupler, was also measured. The results of this test campaign agree very well with the associated simulations and promise a successful and reliable operation of the cavities.arallel to the activities mentioned above, the corresponding beam dynamics layout for the injector part of the HELIAC has been revised for integration into a standalone machine housed in a separate linac tunnel. An ECRIS (Electron Cyclotron Resonance Ion Source) together with a RFQ (Radio Frequency Quadrupole) will supply a beam with $A/Z \leq 6$ to a normal conducting IH (Interdigital H-mode) pre-accelerator unit, providing for beam energy gain from 300 keV/u to 1400 keV/u. The revision of the injector linac allows to re-design the IH cavity using an APF (Alternating Phase Focusing) beam dynamics scheme in order to yield two quadrupole-lens free cavities and to extend the injector with further beam diagnostics and beam steerers. Due to this advanced DTL linac layout, a beam with low emittance growth will be delivered and thus flexible CW operation is ensured. The beam dynamics, RF and thermal design of the APF cavities is already finalized and tendering of the cavities is imminent.

9.3.8 Beam diagnostics R&D towards accelerator operation

Authors: R. Singh, P. Forck, T. Milosic, T. Reichert, B. Walasek-Hoehne

Several R&D activities in beam instrumentation in context of improved accelerator operation were performed in 2021 and some of them are documented [1-5]. We have selected two highlights for this report.

Highlights in 2021

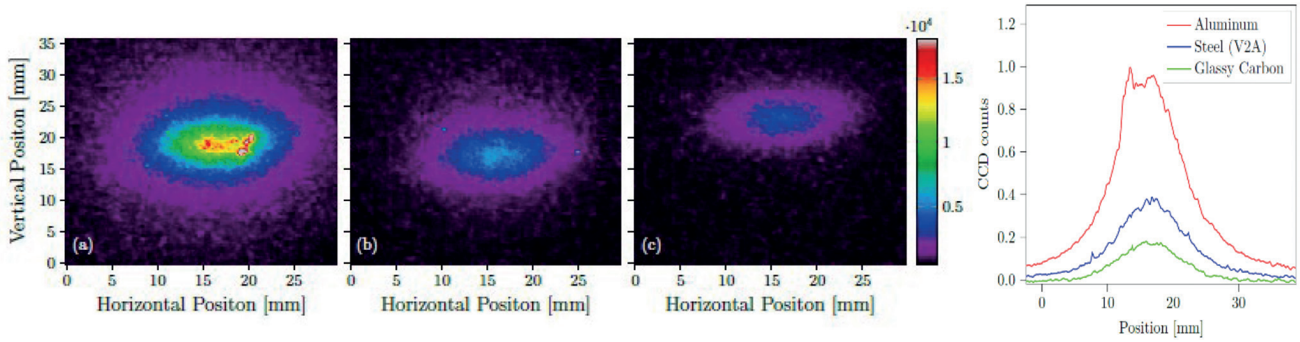

Figure 79. (Left) The OTR image obtained after averaging 200 images for ~5.109 Ca10+ ions incident on (a) Aluminium, (b) Steel (V2A) and (c) Glassy carbon target; the colorbar is the same for the three images to highlight the relative intensities. (Right) The horizontal projection of the images; the number of emitted photons are expected to be proportional to the reflectivity of the target material and the measured relative photon yields are in line with the analytical estimates [1].

The measurement of the 6D phase space presents unique challenges for non-relativistic heavy ion beams. A conclusive study on the usage of optical transition radiation for transverse profile measurement for various targets including non-metallic substance such as glassy carbon was performed. Figure 79 shows the measured profiles for three target materials under the same beam conditions as marked in the caption. The relative light output is in expectation with theoretical estimates. A notable observation of an anomalous increase in emitted light for grazing incident angles on the target was encountered, which is postulated to be the effect of surface roughness discussed further in [1]. A set-up for single shot-by-shot longitudinal charge distributions using the GHz component of transition radiation (GTR) was also demonstrated [2].

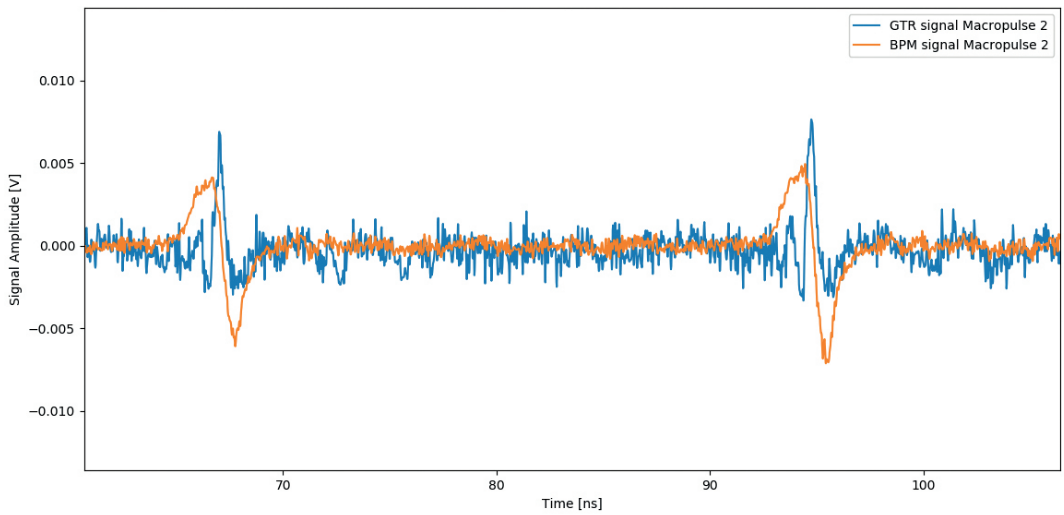

Figure 80. Two consecutive bunches measured in the X2 beam line-by both monitors for a Bi^{26+} beam at beam current of 0.4 mA.

Figure 80 shows the signal induced on a GTR monitor and the capacitive pick-up 1.5 m upstream of the GTR monitor for a 100 us pulse of 11.4 MeV/u Bi^{26+} beam. The pick-up signal is scaled down by a factor of 10 to allow for sufficient visual comparison. The double peak structure within a bunch seen in the GTR signal is lost in the pick-up signal due to a field elongation of the non-relativistic beam.

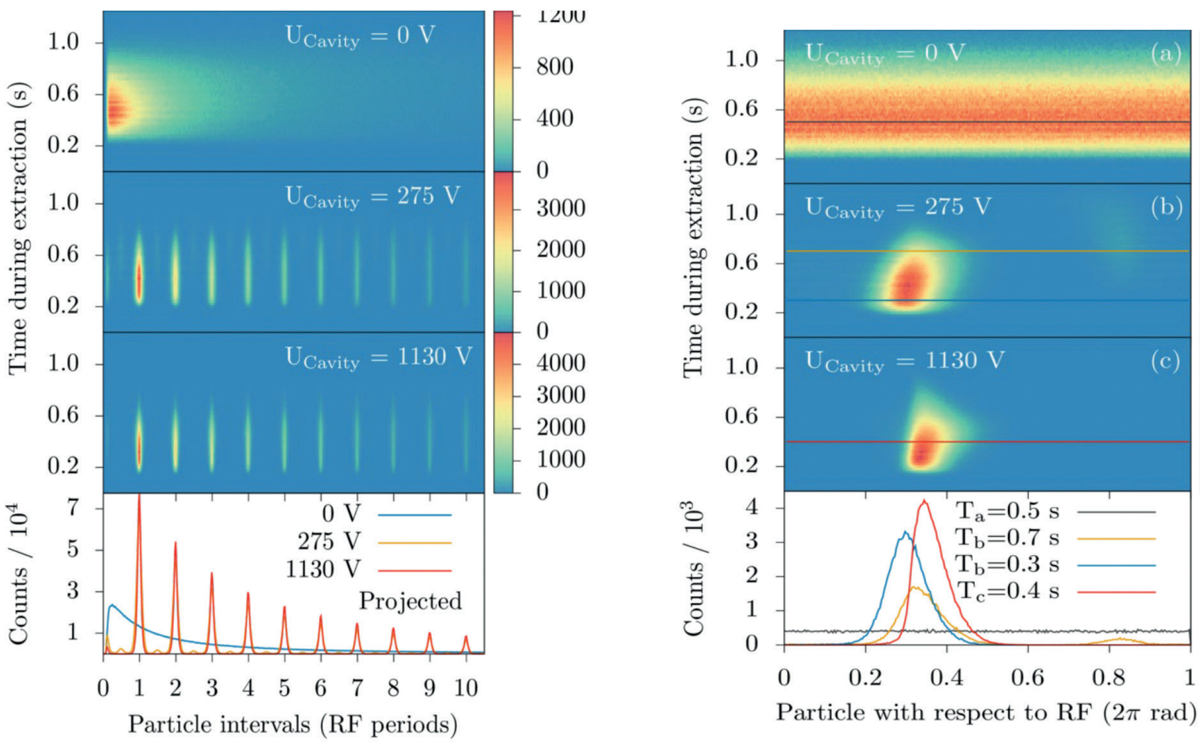

Figure 81. Time between subsequent particle arrivals (left) and the time difference between particle arrival and the previous RF pulse (right) for ~1.2.10[6] Bi^{68+} are shown for various cavity voltages; the colorbar represents the count. The projection of the images is shown on the lowermost plot.

The second major activity was on the synchrotron side, where a new data acquisition system for fast time to digital converter (TDC) was developed and put into operation for bunched beam extraction diagnostics. In Figure 81 some results are depicted, (left) showing the histogram of particle intervals. It was observed, that most particles are extracted from neighbouring buckets, when the cavity frequency is higher than the extraction rate. In Figure 81 (right) the histogram of the particle arrival with respect to the cavity RF signal is depicted. Particles are extracted from a smaller part of the RF bucket than occupied by the circulating beam in the synchrotron, which is a consequential result for many fixed target experiments.

Outlook for 2022

OTR investigations will continue in order to make them operational. The TDC DAQ has been commissioned in regular operation and is now available for spill diagnostics; it would be useful especially for bunched beam extraction.

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9.3.9 FOUROSE – site acceptance test of a 4d-emittance scanner software

Authors: M. Maier, X. Du, P. Gerhard, L. Groening, C. Xiao, A. Bechthold, J. Maus (NTG, Gelnhausen, Germany)

FOUROSE [1] is a software package being developed to guide the user through the process of measuring the four dimensional transverse properties of heavy ion beams using the detector setup ROSE [2]. This contribution reports on the successful site acceptance test at GSI.

Introduction

ROSE is a patented ROtatable Scanner for Emittance measurements and allows determining the full four dimensional transverse ion beam matrix as described in detail in [3]. ROSE consists of the detector hardware itself, housed within a rotatable chamber, the fully standalone electronics rack ROBOMAT, to perform the individual emittance measurements [4], and the software package FOUROSE that guides the user through the complex process of 4d-emittance measurements. The Human Machine Interface HMI of FOUROSE, has been written by NTG and combined with the mathematic codes of GSI. The GUI itself is written in C#, while the CPU intensive mathematical models are realized in Fortran and compiled as dynamic link libraries dll. Off-line test runs and the beam time preparation have been successfully accomplished in 2020.

Experiment

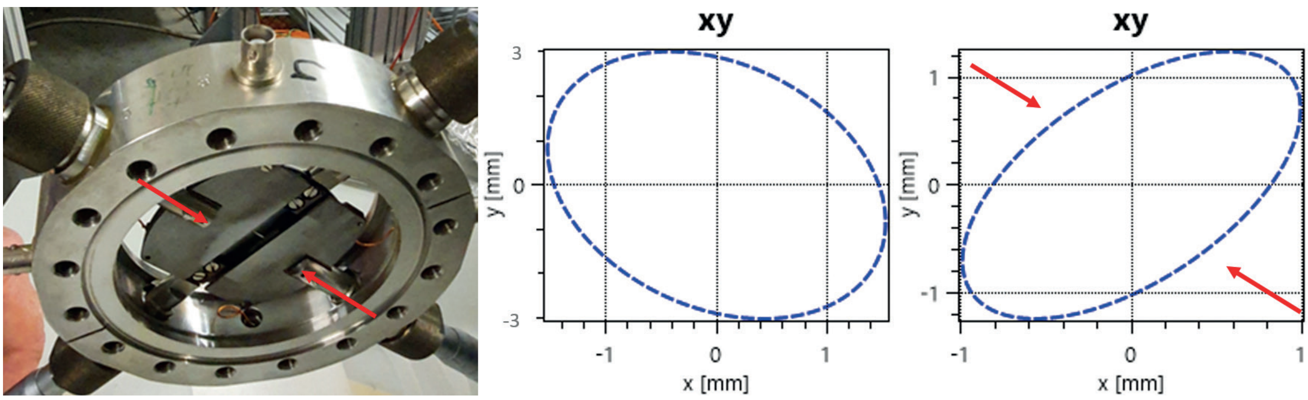

Figure 82. 45° degree slit (left) and the measured xy-phase space projection at the position of the slit for opened (middle) and slit closed to about 60% transmission (right).

ROSE has been setup at X3 behind the magnetic doublet UX3QD6. Additionally to the standard BD equipment, a beam current transformer and an end cup, to guaranty 100% transmission, were added. In the beginning of the beamline just in front of the quadrupole doublet, a by 45° degree rotated slit, to artificially create x/y-coupling has been installed. The beam time was split into two times five days with a two week break in between in order to react to unforeseeable problems. An $^{40}Ar^{8+}$ beam with 8.6 MeV/u and a few 100 eμA intensity has been used for both weeks. Within the FOUROSE software, all three individual parts of the GSI codes are combined within one common GUI, allowing the user to plan, perform, and evaluate 4d-emittance measurements at hadron accelerators. Providing FOUROSE with a horizontal and vertical emittance measurement and the according beamline parameters, it calculated the required magnetic quadrupole settings to get a set of four linear independent measurements for solving the over determined equation system. Using these settings to measure the necessary emittance data, the full 4d-beam matrix at the reconstruction point has been obtained. As reconstruction point, a slit rotated by 45° (Figure 82) in front of the quadrupole doublet has been chosen. To proof the measurement of the 4d-matrix, the slit has been closed to about 60% transmission, and as expected, the slit's imprint has been detected in the x/y-projection at the reconstruction plane.

Conclusion

A 4d-emittance scanner for hadron beams, independent of their kinetic energy, intensity, and time structure, has been invented, built, and successfully commissioned. Together with the industrial partner NTG it has been developed into a commercially available, fully standalone 4d-emittance scanner for hadron beams.

Acknowledgements

Our special gratitude goes to all the excellent people from GSI, HIT, and NTG helping in this project and last but not least the German and Hessian funding agencies.

References

- [1] Dieses Projekt (HA-Projekt-Nr.: 694_19-14) wird im Rahmen der Innovationsförderung Hessen aus Mitteln der LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlichökonomischer Exzellenz, Förderlinie 3: KMUVerbundvorhaben gefördert
- [2] Deutsche Patentanmeldung Nr. 102015118017.0
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9.4 Contribution to the FAIR-project

9.4.1 FAIR commissioning - planning status

Authors: S. Reimann, S. Schumann

Commissioning scenarios

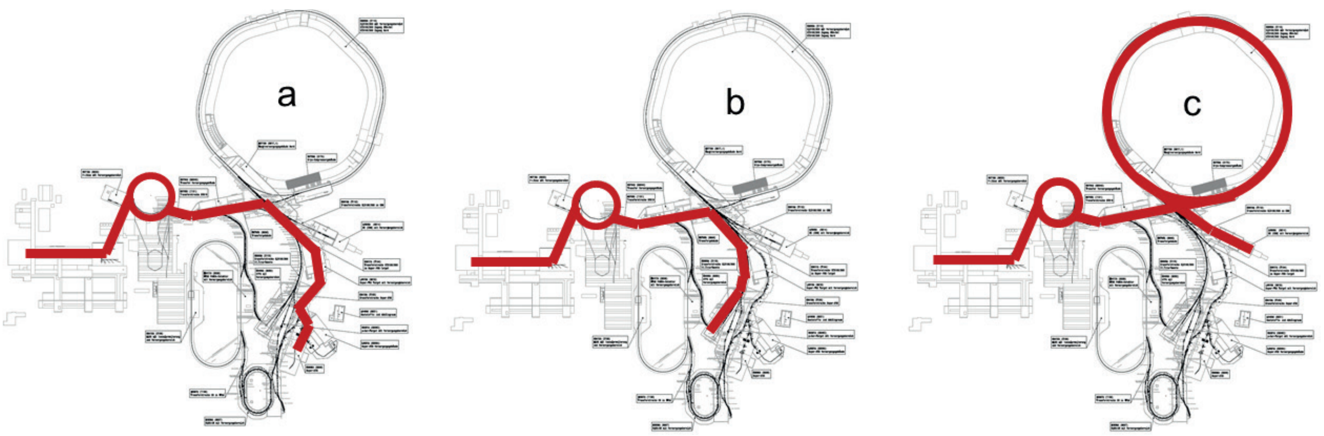

Figure 83. AIR top level scenarios. a) UNILAC-SIS18-SFRS-NUSTAR, b) UNILAC-SIS18-APPA-cave, c) UNILAC-SIS18-SIS100-CBM, Scenarios a) and b) describe the early science objective and scenario c) is considered to complete the FAIR intermediate objective. For the moment, no further intermediate steps are planned before the MSV. It should be mentioned that the first beam is expected to be set to the SIS100 injection dump.

In January 2021, a new FAIR commissioning working group began its work as a collaborative effort with the GSI operations team and the FAIR subproject leaders. The goal was to create an overarching FAIR commissioning concept and a planning strategy. The general procedure is based on the strategic goals of GSI and FAIR and follows a phased approach that is oriented towards a successive development of FAIR operating scenarios. Figure 83 shows the three FAIR commissioning scenarios before the final expansion stage MSV (Modulized Start Version). After completion of commissioning of each scenario, the corresponding accelerator chain is ready for operation and will be available for first physics program in parallel to further beam commissioning within certain limits. Parallel operation of the existing GSI accelerator facility is also planned to a certain extent.

Planning strategy and commissioning phases

#	commissioning stage	accelerators & transfer lines	detectors
1	local hardware commissioning	• local system tests in tunnel and supply areas • control system not available (only limited aspects) • media needed – temporary supply is sufficient	• single detector tests • individual components • install. service & controls
2	remote & system commissioning	• single system tests (vertical integration tests) • remote testing from Main Control Room (sequencer tests) • full controls system integration of the system and timing available, TBI & media supply fully available	• system tests (with HV, gas, ...) • pre-test of DAQ system • local control
3	integration	• (3.1) multi system tests • (3.2) full dry-run of pilot beam scenarios	• full detector test and DAQ using cosmic particles
4	pilot beam commissioning	• commissioning with pilot beam	• commissioning with pilot beam

Table 3. FAIR commissioning phases.

Separate commissioning plans were created for all subprojects and set of general commissioning stages (Table 3) were defined. These stages are applied at all four planning levels (1. scenarios, 2. accelerators/detectors, 3. sections, 4 systems) and support a common understanding of the stage transitions and milestones for both the accelerators and the detectors.

The commissioning plans were generated in agreement with the 2021 project baseline and contain the above-mentioned structure with all links and dependencies for which information is currently already available within the FAIR project planning. Further detailing is currently being carried out with the specialist groups in so-called Lean Commissioning Workshops (LCM), in which the commissioning processes for each of the approx. 100 FAIR system types are discussed with the specialist experts, written down and combined with information on resource requirements. A secondary goal is the preparation of the generation of automatable commissioning sequences. The planning process is expected to be completed in the course of 2022.

It became apparent that more complex common systems, such as the accelerator control system and cryo distribution, need to be planned at a higher level. For this reason, both systems are planned separately from the subprojects, and the planning of the control systems is accompanied by a specially established control systems steering group. This steering group carries out an assessment of the main software projects against strict criteria, with the aim of prioritizing the development of the control systems to align it with the high-level commissioning scenarios.

9.4.2 High current ion sources development for FAIR

Authors: A. Adonin, R. Hollinger

The development of high current ion sources continuously progresses. In 2021 the activities were focused on the upgrade of MUCIS-2010 (MUlti-Cusp Ion Source 2010). MUCIS-2010 is a volume type gaseous ion source designed for operation with heavy gases (Kr, Xe). One of the requirements of injection into the HSI-RFQ (radio frequency quadrupole) for heavy ions is that the mass-over-charge ratio (M/q) of the ions must be below 65. That means, for operation with Kr-isotopes it is necessary to produce double-charged ions (Kr^{2+}) and for operation with Xe-isotopes – triple-charged ions (Xe^{3+}), respectively. An exception is the Xe-124 isotope, here the operation is possible also with Xe^{2+} ions (if HSI is fit to work stable with high RF-level).

For volume type ion sources charge state 1+ provides maximum intensity. To shift the distribution maximum to higher charge states and, consequently, to increase the production efficiency of the desired multi-charged ions, one needs to squeeze the plasma plume in the ion source with a strong longitudinal magnetic field. For this reason MUCIS-2010 is equipped with an outer solenoid. To increase the performance for Xe^{3+} ions it is necessary to increase the solenoid field, which is limited by the capability of the power supply as well as by the thermal load of the solenoid itself.

The first part of the MUCIS-2010 upgrade was rewinding of the solenoid. A Cu-wire of ø2mm has been used to replace a ø1.3mm wire. The new solenoid has a double layer of windings instead of a single layer in the old one. The number of windings in the solenoid was increased from 159 to 190. These measures have allowed to reach the same magnetic field in the solenoid with notably lower electrical load (65V / 33A instead of 150V / 40A), to reduce the thermal load on the coil and to extend the working region of the solenoid.

The second part of the MUCIS-2010 upgrade was an enhancement of the extraction system. The standard triode multi-aperture extraction system with 13-holes / ø3mm has been replaced by a 7-holes / ø4mm extraction system with improved geometry of the electrodes. The total extraction surface was reduced from 0.92cm^2 to 0.88cm^2. This reduces the maximum extracted ion beam current from the ion source. But at the same time, the outer diameter as well as the transversal emittance of the extracted ion beam are also reduced, which results in a higher beam brilliance and higher transmission in the subsequent sections of the UNILAC [1].

In November 2021 the upgraded setup of the MUCIS-2010 has been tested on Terminal North. The tests have been performed with Kr and Xe gases, recording analyzed beam currents as well as mass-spectra in the UH1-section of the HSI-LEBT (low energy beam transfer line). Settings for LEBT magnets have been used from the beam time 2020 for isotopes Kr-86 and Xe-124, corresponding to optimized beam transmission through the UNILAC. As a result of the tests, the following ion beam currents have been reached in UH1-section: 9.4mA of Kr^{2+}, 13.5mA of Xe^{2+} and 4.3mA of Xe^{3+}. Based on these test results the setup upgrade will be implemented also to other MUCIS ion sources.

Another highlight of 2021 from high current ion sources was a successful long-term test of uranium operation for FAIR in the booster-mode [2]. In the booster-mode the ion source produces 4 U-beam pulses during 1.1s (which corresponds to 2.7Hz operation) and then stays in standby for the delay-time (τ) till the next request. The test has been performed with the VARIS (Vacuum Arc Ion Source) on Terminal North in December 2021. The ion source was operated with best performance, providing up to 17mA of U^{4+} ions in the UH1-section. Three U-cathodes have been tested for a full lifetime. Two operation modes have been checked during the test: with τ = 6s and τ = 3s. In both cases stable operation was demonstrated with low rate of cathode ignition failures. The approximate lifetime of a single cathode in booster-mode amounted to ~18 hours with τ = 6s and to ~11 hours with τ = 3s, respectively.

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10. Research in accelerators, detectors, electronics and IT

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

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

Head: Dr. Peter Spiller (GSI)

SIS100 laser cooling pilot facility

Authors: S. Klammes[1,2], M. Bussmann[3,4], K. Ebenholz[5], J. Gumm[2]; V. Hannen[5], D. Kiefer[2], T. Kühl1,6, B. Langfeld[2], P. Spiller[1], U. Schramm[3,7], M. Siebold[3], T. Stöhlker[1,6,8], T. Walther[2,9], and D. Winters[1] (correspoding author),
1 GSI; 2 TU Darmstadt; 3 Helmholtz-Zentrum Dresden-Rossendorf; 4 CASUS Görlitz; 5 Münster University; 6 HI Jena; 7 TU Dresden; 8 Jena University; 9 HFHF Frankfurt/M

Figure 84. The left part shows the SIS100 construction site, the middle parts show the SIS100 laser beamline and its support, and the right parts show transport to and lifting tests in the ESR hall (and the safety hats).

The FAIR synchrotron SIS100 will be the worldwide first and only user synchrotron equipped with a facility to cool accelerated heavy-ion beams at final energy by means of lasers [1]. The goal of the work package 'SIS100 laser cooling', which is part of the FAIR subproject SIS100, is to build this facility and to start cooling right after the com-missioning of the SIS100 (in 2026) [2]. We gratefully acknowledge the excellent support from POF III/IV ARD (accelerator research and development) subtopic 2 in the Helmholtz program “Matter & Technologies”.

The most important milestone of our working group in 2021 was to install and test the first part of the laser beamline at the SIS100 construction site, see Figure 84. This 13 m long beamline weighs about 300 kg and consists of two concentric stainless steel tubes (DN160CF inside DN200CF) and can be evacuated down to 10^{-6} mbar. (The outer tube serves as a safety tube, just in case the inner tube would causes problems, but it has the same quality as the inner tube.) The beamline will connect the maintenance tunnel to the accelerator tunnel and must be installed during the construction phase of the tunnels. The beamline was designed by the GSI mechanical design office, built by the GSI mechanical workshop, vacuum tested by the GSI technology laboratory and transported (on cam-pus) by the GSI transport and installation group. Transport to and installation at the FAIR SIS100 construction site commenced in January 2021 and was coordinated by FAIR/GSI site management and carried out by the civil contractor PORR.

After installation in the SIS100 tunnels, the exact position of the laser beamline was measured and a vacuum test (of the inner tube) was performed on site. After these tests, the laser beamline was poured over by concrete and its position fixed forever. During the following construction and installation phases in the SIS tunnels, both ends of the beamline will be protected by two safety hats. The rest of the laser beamline will be installed after the tech-nical building installation is completed.

In May 2021 there was a “GSI beam experiment” at the ESR for laser cooling of Li-like carbon ions ($^{12}C^{3+}$). We have successfully – and for the first time – performed bunched ion beam laser cooling with a high repetition rate (10 MHz) high power tuneable UV laser system from the TU Darmstadt [3]. Besides the very high repetition rate, also the variable pulse duration (166 – 740 ps) of the laser system could be demonstrated for the first time during such an experiment. Special focus was also put on ion bunch – laser pulse synchronisation, which will also be very important for laser cooling at the SIS100. Finally, improvements of the (in vacuo) XUV fluorescence detection system from Münster University were tested [4]. Fluorescence detection is an important tool for future experiments at GSI and FAIR, but therefore the background (produced by the ion beam and by the laser beam) must be well under control. We were able to reach all the goals of the beam experiment and it was a great success.

- [1] D. Winters et al.: Laser cooling of relativistic heavy-ion beams for FAIR. Physica scripta T166, 014048 (2015) DOI:10.1088/0031-8949/2015/T166/014048
- [2] D. Winters et al.: The SIS100 laser cooling facility. In: GSI-FAIR Scientific Report 2019 (p86-87) DOI:10.15120/GSI-2020-00416
- [3] D. Kiefer: Ultraviolet lasers for cooling of relativistic ion beams. PhD Thesis TU Darmstadt (2019).
- [4] D. Winzen et al.: Commissioning of a detection system for forward emitted XUV photons. In: GSI Scientific Report 2016, Research-APPA-AP-20 (p245) DOI:10.15120/GR-2017-1

10.2 Activities of the Department Experiment Electronics

Head: Prof. Dr. Peter Braun-Munzinger (GSI)
Author: Nikolaus Kurz

Various new developments from the department for Experiment Electronics (EEL) enabled the experiments at FAIR Phase-0 to conduct their successful data taking in 2021 beam times. On the hardware side this comprises new ASICs, analogue and digital electronics developments and the in house production of numerous electronic boards. On the software side EE provided its data acquisition (MBS, DABC) and analysis systems (GO4), which were enhanced with new features to cope with the ever increasing demands of the experimental setups towards FAIR. In addition, the EE lab was equipped with new devices to further improve production and test capabilities.

Highlights in 2021

Deployment of a Laser Cutter System in the EE Laboratory

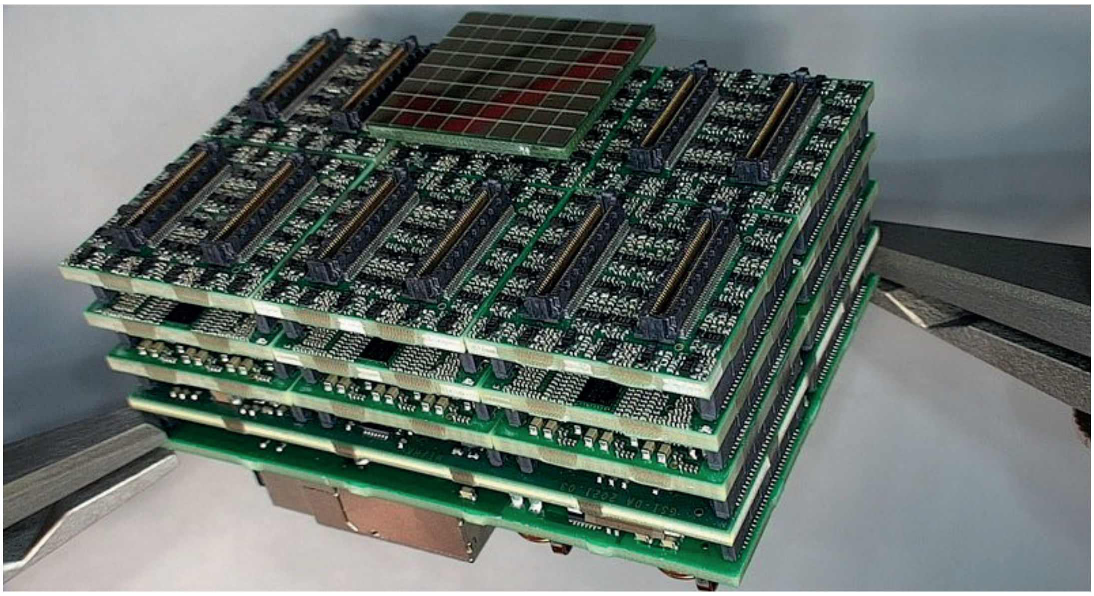


Figure 85. HADES FaRICH: Full readout system for 384 channels of SiPM. Please note the dimensions of 53 mm x 81 mm x 38 mm. Only one out of 6 SiPM arrays mounted.

For the first time a Laser Cutter system was deployed at EE. It provides a wide range of new possibilities for developments and production, e.g. rapid proto typing of simple printed circuit boards (PCB), or cutting of materials in sophisticated shape. One main field of application is the cutting of PCB after parts mounting. Due to space limitations parts have to be mounted extremely close to the edge of PCB. It has been proven that the final cutting of PCB fails with traditional mechanical devices, by destroying PCB and ripping off parts. With the Laser Cutter this can be performed with excellent results without problems. See in Figure 85 as an example the high density stack of PCB for the HADES FaRICH.

TwinPeaks (TP): a high resolution charge to time amplifier for DESPEC

The new TP is a charge to time amplifier for the FATIMA LaBr used by the DESPEC experiment [1]. It features two electronics channels per signal input, one with logarithmic characteristic and the second with linearized charge to time output. Connected to the high resolution FPGA TDC TAMEX4, it allows for the simultaneous time (11 ps RMS) and spectroscopic energy measurement (30 Kev – 1.5 MeV gammas). An additional feature of the TAMEX TP system is a threefold accepted trigger and event rate, compared to the previously used VME system, with identical energy precision and four times better timing precision. Exceptionally long trigger windows of 330 us made it possible to record physics processes, e.g. beta delayed gamma emissions, in single events. With appropriate pre-amplifiers the TP TAMEX4 was also used to readout the detector measuring electrons from beta decay in DESPEC, equipped with Silicon Photo Multipliers (SiPM). In principle the TW is suited to readout other SiPM based detectors.

KILOM: a full readout system for the scintillating fiber detectors for R3B

Various new types of scintillating fiber detectors at the R3B experiment required a high density and many channel readout system, which was accomplished with the newly developed KILOM FPGA TDC readout system. It is composed of a frontend and main board. Each frontend board has 128 input channels, is equipped with PADI pre-amplifier chips and plugged directly in the Multi Anode Photomultiplier (MAPM, 16 x16 array) of the fiber detector. Two frontends serve one MAPM. The main KILOM boards are also connected to its associated frontend without cables. Heart of the KILOM main board is a 128 channel FPGA TDC with a timing precision of 170 ps. The full data transmission path from the MAPM to the data acquisition system requires no copper cable, instead the data is sent from the KILOM via optical transmission to the readout pc. In total 70 KILOM, close to 9000 input channels, have been provided. The first experiment utilizing the KILOM system was the "Coulomb Dissociation of ^{16}O into ^{12}C and ^{4}He". Further systems of these types are in production for the WASA setup for beam times in 2022.

FaRICH: a compact SiPM readout system for HADES

The aforementioned new FaRICH system for HADES (Figure 85) stands out for its extreme small space occupation. The volume occupied by electronics boards could be reduced to a fraction of 10 with respect its predecessor DiRICH. Despite its compactness it comprises full analogue and digital treatment of the SiPM signals and an integrated data acquisition system in a stack of 4 PCB plus the SiPM arrays. In a volume of 53 mm x 81 mm x 38 mm 384 SiPM channels are readout. Timing precision is 10 ps. Furthermore, the geometry of the new FARICH allows for the arrangement of SiPM arrays with virtually no gaps.

IFC: a VME readout processor for MBS

Beginning of 2021 the production of the VME Processor board RIO4 was stopped without announcement. It was (and still is) the working horse for all VME based MBS data acquisition systems at GSI. More than 70 RIO4 are currently in operation and are mandatory for many FAIR Phase-0 Experiments.

A survey of available VME processor board revealed the IFC from the company IOxOS as a candidate with similar performance characteristics as the RIO4. It has now been basically integrated into the general purpose data acquisition system MBS of GSI. The implementation of the VME WHITE RABBIT time stamping board VETAR is currently ongoing. Afterwards the IFC can be used as a full replacement of the RIO4.

Online Experiment data storage LTSM

The new DAQ storage interface LTSM/FSQ has been further improved in the scope of the HADES experiment. This development (together with the GSI IT department) allows to transfer raw data files from the data acquisition event builders with minimal delay both to the Green IT-Cube / lustre storage and to the TSM tape library. During HADES test beam in 2021, this system has been used within the DABC DAQ software for data taking. Here a total data rate of up to 1 GByte/s could be achieved when writing 10 parallel event builder files. It will be applied for the HADES production beam time S518 in February 2022.

ASIC developments

Three new ASIC chips have been developed and produced.

- ATR16: A 16 channel hit detection and readout chip to be used for the PANDA Barrel electromagnetic calorimeter.
- CTR16: A prototype of a 16 channel hit detection and readout chip for the Super FRS GEM TPC Tracking detectors.
- AWACS: A charge sensitive preamplifier with automatic gain adjustment covering a large sensitivity ranging from 0.5 fC to 50 pC, It is integrated into the POLAND beam diagnostic devices for FAIR and its main purpose is to detect very low intensity pilot beams. In addition a modified version is intended to be integrated into the CTR16 for the Super FRS GEM TPC Tracking detectors. These devices have to cope with a large charge detection range due to the usage with beams of particles with low up to highest Z.

10.3 Activities at the Department Detector Laboratory

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

Activities at the detector laboratory were heavily focused towards the completion of FAIR detector systems and support for beam times within the FAIR Phase-0 program.

The developments towards an LGAD-based time-zero detector for CBM and HADEs have been very successfully advancing. A batch of large 20mm x 20mm strip structured LGAD sensors of 200μm (50μm active) thickness were produced at Fondazione Burno Kessler (FBK, Trento) and evaluated in various beam times at COSY (FZ Jülich) and MedAustron. With the proven time resolution below 50ps the system is now being employed as time-zero device in an active HADES production run at 10^8 protons/s and a signal rate of 10 MHz per channel.

At mCBM, the FAIR Phase-0 test and validation facility for CBM, detector modules of the CBM Silicon Tracking System (STS) have successfully been tested with several modules in concert in a real particle tracking configuration. Tracking of secondary particles could for the first time be realized all the way back to the heavy ion interaction point. This important achievement for the CBM-STS also verifies that module serial production is feasible at DTL, one of the three STS detector module assembly sites. The preparation of this serial assembly activity is a mayor activity at DTL and will lead to an extended project for the CBM-STS.

To strengthen the GSI assembly site, two new fully automatic bonding machines could be added to the DTL machine park. They will allow for a streamlined assembly of STS detector modules but also with a mid-term perspective strengthen the technical capabilities at DTL to-wards handling, integration and interconnect of MAPS CMOS pixel sensors in their challeng-ing appearance ultra-thinned to below 50μm thickness. DTL participates in the developments that aim to eventually assemble waver-scaled versions of such sensors in a self-supported, bent configuration. With the new bonding machines, also Gold ball-wedge bonding and Gold bump bonding will be feasible at DTL.

Beyond CBM-STS the bonding laboratory supported two other projects: the STRASSE detector (TU Darmstadt) and the ALICE ITS upgrade (in cooperation with Univ. Heidelberg).

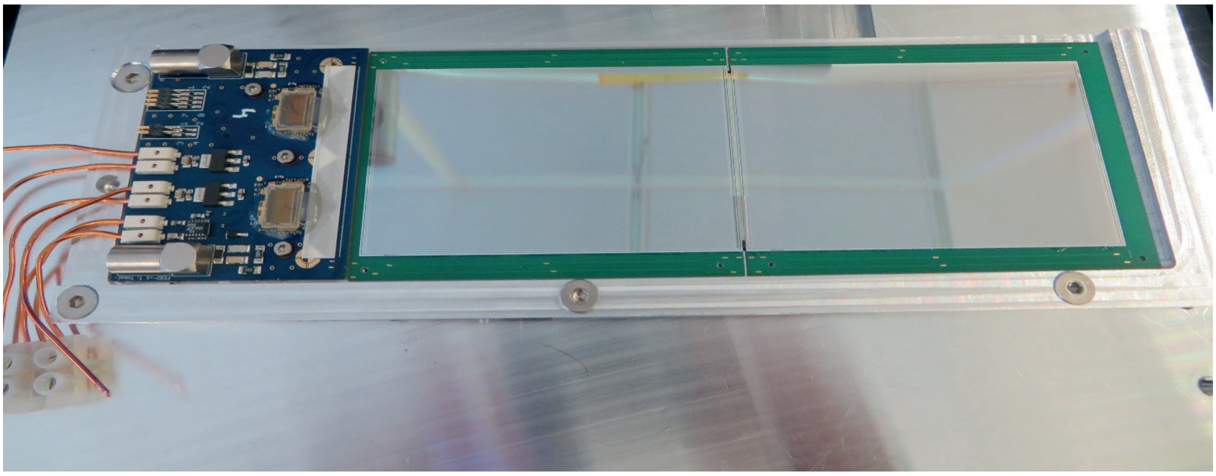


Figure 86. Prototyping Silicon Detector Module PFAD. Sensor dimension in the assembly is 60 mm x 200 mm.

The STRASSE detector is a silicon tracker for quasi free scattering at the RIBF. DTL assem-bled PFAD modules for first tests towards STRASSE. Two front end boards with 2, respec-tively 6 STS-XYTER-ASIC´s were wire bonded for the readout of the silicon sensor micro strips (see Figure 86). The elaborate wire bonding connects two daisy-chained sensors on a frame to the respective readout ASICs. Additionally, every two neighboring strips are con-nected to obtain the appropriate pitch. The combined strips are then connected to pitch-adapters on the front end boards and eventually to the readout ASICs.

For STRASSE, the final detector system, the sensor strips will be connected to the front end board by means of ultra-thin micro cables provided by the unique company LED-Technologies of Ukraine (LTU). The corresponding bonding technology is TAB-bonding. LTU´s micro ca-ble technology is the ultra-low mass analogue cable technology widely employed for the assembly of the CBM STS.

Both the CBM STS-XYTER readout chip as well as MIMOSIS-I, the prototype CMOS pixel sensor for the CBM Micro Vertex Detector (MVD) were successfully tested for their sensitivity to singe event upsets (SEU) when exposed to heavy ion Xenon and Lead beams.

With the first full size prototype chip MIMOSIS-I available it could fully be characterized in various beam times at DESY, CERN and GSI as preparation for the next prototype version of a near to final design. The tests allowed to make important choices on design alternatives within the sensor chip.

Infrastructure used in the cleanroom for the production of Scintillating Fiber Tracking Detec-tors has been established. Five detectors were built in 2021 for the R3B experiment and have successfully been employed for physics experiments in the same year. The detectors are based on single layer fiber ribbons using fibers of square cross section with a width of 250µm and 500µm respectively. This unique tracker design was optimized for a homogeneous and mini-mized material budget. Scintillating fibers are read-out using Hamamatsu Multi Anode PMTs coupled to the chain of the preamplifier and discriminator front end ASIC PADI and an FPGA TDC.

The construction of several Multi Sampling Ionization Chambers serving the need for stand-ardized energy-loss measurements at the Super Fragment Separator focal planes has been started as Finnish in-kind contribution to FAIR, that GSI was contracted for. The first of se-ries device meant to be installed at the internal focal plane FMF1 in the main separator is cur-rently being assembled for tests and in-beam commissioning in 2022.

A successful test of a potential candidate for the readout of the GEM-based Tracker 'GEM2D' designed for the target spectrometer of PANDA has been performed late 2021 in close cooperation with CERN's RD51 collaboration. It is based on the VMM3 chip which was integrated into RD51´s scalable readout system SRS. Further commissioning is foreseen in 2022.

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

Based on the R&D performed in 2020 DTL could build and mount new electrodes, a vacuum and pumping system as well as new front-end electronics to the high-pressure time projection chamber that will act as an active target IKAR. The new PLC-based gas filling and monitor-ing system was developed and assembled. The entire setup was tested in a pilot run together with the AMBER collaboration at CERN. Data analysis is ongoing but first observations con-firm the feasibility of the Proton Radius Experiment using this concept. The design of the main TPC detector is aimed to handle high rates of charged particles for the experiments at CERN and FAIR. System construction will be done until the end of 2022.

Together with the R3B and the SuperFRS collaboration, new large-area silicon micro-strip detectors were built and tested using cosmic rays. Originally developed at INFN Perugia, these detectors allow particle ID and tracking at higher particle rates and larger angular coverage as it was possible before. Test experiment at COSY (FZ Jülich) using a proton beam with different energies and intensities were performed for the characterisation of the detectors. 10 detectors of this type are planned to be used in two experiments within the R3B setup in 2022.

Testing of the ALPIDE Silicon CMOS pixel detectors using a high-rate muon beam at CERN was performed. Different readout modes, cooling and mounting concepts were investigated. A new tracking station with 18 sensors, thin flex boards using SpTAB-bonding technology and a carbon-fibre cooling plate has been developed. First tests of the station are planned in 2022 in cooperation with SuperFRS, R3B @ FAIR and the AMBER CERN collaborations.

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

For the CBM transition radiation detector (CBM-TRD) samples of newly employed materials were tested and verified for their use in gaseous detectors.

10.4 Research of the IT Department

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

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

Highlights in 2021

Virgo cluster

The high-performance compute cluster Virgo has been extended by 400 AMD Radeon InstinctTM M100 Accelerators. The new GPUs were installed and configured and finally made available for the users in the last quartal 2021. Moreover, work has been continued to improve the quality of server on the cluster, i.e.: a new set of tools (MPI-Based) was implemented to check/monitor the operation and efficiency of the cluster.

Software development for online data processing

At the GSI, a new Cluster controller for CBM is being developed based on the Online Device Control (ODC) package, DDS and FairMQ (see M. Al-Turany et al. ALFA: A framework for building distributed applications. EPJ Web of Conferences 245, 05021 (2020) DOI:10.1051/epjconf/202024505021). The proto-type was tested during the beam time of mCBM. In October 2021 the first pilot beams were received from the LHC at the ALICE detector, The pilot beams are part of the commissioning of the LHC machine in preparation for its Run 3 in 2022. The tools developed at GSI for the future FAIR experiments and ALICE where successfully used/tested during the beam time.

Lightweight Tivoli Storage Management (LTSM)

Besides the long-term archive of experiment data to a magnetic tape library, many experiments required to process this data as soon as possible on the high-performance compute farm. For solving this challenging requirement, a new framework (called LTSM) for efficient and robust data transfer to archive system has been developed. HADES experiment adapted and used this framework also in the last beam time in February 2021. For other GSI/FAIR experiments using the vintage MBS ("Multi Branch System") event builders, an LTSM gateway application has been developed to connect the legacy RFIO ("Remote File I/O") protocol of these DAQ systems with the new storage interface (see Jörn Adamczewski-Musch and Thomas Stibor. Mass storage interface LTSM for FAIR Phase 0 data acquisition. EPJ Web of Conferences 245, 01018 (2020) DOI:10.1051/epjconf/202024501018).

ESCAPE project

For the WP2 in ESCAPE project, the most important milestone in 2021 was the Data Analysis Challenge (DAC21). To prepare for it, the GSI-IT and members of the experiments CBM, PANDA and R3B worked together to prepare realistic use cases for a Data Lake. These use cases were then run during the DAC21, both on the cluster and on local machines, reading and writing data from the Data Lake. In WP3, Software packages FairRoot, FairMQ, DDS and R3BRoot were onboarded to the ESCAPE Open-source scientific Software and Service Repository (OSSR), thus making these packages available for the whole community.

10.5 Activities in technology transfer at GSI and FAIR

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

The Technology Transfer Department (TTR) is a staff unit reporting directly to the Administrative Management. With six FTE, of which three FTE are financed by third-party funding, TTR is responsible for the processing of services and contract research, innovation management, business development and technology marketing

Highlights in 2020

Transferstrategy

The transfer strategy developed in 2020 with defined goals and measures was officially adopted by the GSI Supervisory Board in June 2021. The central task of this strategy is to increase the social benefit of scientific results and technologies. For the GSI, this means on the one hand the transfer of research results and interpretative knowledge to society, politics and the economy; on the other hand, knowledge and technology transfer provide additional value contributions to the current strategic goals of the centre. Derived from this, the measures focus on the technical utilisation and commercial exploitation of scientific results from research and technological developments from the operation of the facilities.

The following measures are available for exploitation:
- Transfer via information,
- via cooperations,
- via industrial property rights and other intellectual property
- via brains and
- via start-ups

GSI pursues three main goals with this strategy:
1. creating a culture of innovation by promoting awareness and understanding of transfer options.
2. optimising and strengthening transfer activities, creating an effective transfer structure using adequate resources.
3. development of indicators and monitoring of transfer activities to analyse the impact of transfer instruments.

The transfer strategy comprises 21 measures, divided into short, medium and long-term actions. The introduction of an innovation fund an establishment of an innovation board are short term measures and are considered very important. The GSI/FAIR Innovation Fund is an essential instrument for supporting technology transfer and establishing effective transfer structures at GSI and FAIR. The Innovation Fund is used in particular to finance the product-oriented validation and further development of market-relevant technological potential from research and development at GSI and FAIR. The main objective of the GSI/FAIR Innovation Fund as an internal funding instrument to improve funding opportunities for technology transfer projects at GSI/FAIR and to create a resource for transfer projects. As a secondary objective, the establishment of the centre's own innovation fund is also expected to have a positive effect on further strengthening the innovation culture at the centre.

The GSI/FAIR innovation fund is intended to ensure that transfer ideas with potential are transferred to a state in which direct utilization or follow-up financing of further development/validation with external funds is possible. The current transfer potential of GSI/FAIR should thus be better exploited and expanded on long term. In addition, own funds for improved cooperation with industry in joint R&D projects and strategic partnerships are provided or spin-offs might be enabled.

The basic prerequisite for the Innovation Fund is the sustainable provision of financial resources: At GSI, a return flow model was established by which funds from existing transfer activities like licensing revenues, contract research, sales and services, are partially redirected into the Innovation Fund. This return flow concept is the basis of the Innovation Fund principle: innovative projects receive funding with the aim of generating returns for the scientists, the institutes and the Innovation Fund. Since March 2022, the internal innovation fund has been supplemented by additional funds requested from the Helmholtz Association.

Parallel to the introduction of the Innovation Fund, an Innovation Board was initiated. The Innovation Board currently consists of 14 people and bundles the diverse interdisciplinary expertise of GSI/FAIR.

The Innovation Board makes decisions on the following topics:

- Recommendations on claiming of inventions, patenting of inventions, abandonment or sale of property rights as well as exploitation strategies for the respective inventions to the management.
- Recommendation on the use and application of technologies
- Evaluation of applications to the Innovation Fund
- Selection of the Annual Innovation award

In addition, the Innovation Board advises the GSI management on strategic issues of technology transfer, e.g: proposing new instruments, methods or incentives to strengthen the innovation culture. The first constituent meeting of the Innovation Board took place in January 2022.

Open X

As part of a BMBF-funded exploratory project on Open Science, the effects of Open Science strategies on the technology transfer activities of German research institutions are being investigated together with the HZDR -Helmholtz Centre Dresden-Rossendorf and the IPHT - Leibniz Institute for Photonic Technologies. In the frame of this project approaches have to be identified and developed that enable successful knowledge and technology transfer under the framework conditions of Open Science.

- This will be done by the empirical description of challenges in knowledge and technology transfer (KTT) of university and non-university research institutions due to the impact of Open Science strategies;
- the identification of solutions for dealing with the above problems; and
- the initial exploration of solutions that may already be in practice.

The exploratory project is being used to prepare a further research and development project, which has been submitted as an application to the BMBF: Open Transfer- Strategies for the Transfer of Research Results in the Open Science Context.

The aim of the Open Transfer project is the development and testing of new methods for the better transfer of knowledge and technologies in the context of Open Science and with a differentiated understanding of Open Science and transfer, in particular new

- strategies and business models for transfer,
- tools for concrete and simple support of transfer processes, as well as
- organisational structures and processes for integration into the activities of the respective research institutions.

Transfer in the sense of the above objective includes any use of research results outside of scientific applications, either in the form of commercial exploitation, or making them available completely free of charge or hybrid approaches where, depending on the purpose and type of use, different or no consideration is required.

In the context of open science, this means that research results already generated and exploited under open science conditions and those generated in the classic, closed system are considered, but which are to be made accessible under open(er) conditions after a certain point.

Transfer projects ROSE and ROBOMAT

A successful transfer project since 2019 is the development and marketing of the emittance scanner “ROSE”. ROSE is an emittance measurement system that is independent of location and control system. In addition to the commonly used measurement of the two-dimensional (2d) distribution of an ion beam, ROSE measures the full four-dimensional (4d) distribution. A medium-sized company was won as a cooperation partner for an industry-compatible development, production and ultimately also worldwide marketing. In addition, third-party funding (120T€) was successfully obtained for this project from the Ministry of Economics via the funding instrument “WIPANO” with the aim of achieving market entry in 2022.

With support from the Hessian funding initiative LOEWE (>550T€) in cooperation with the company NTG - Neue Technologien GmbH in Gelnhausen, a software package is being developed and will tested together with previously developed components ROSE detector and the electronic control system “Robomat” as a prototype of the 4D emission system “ROSE”, which later will be used for routine operation at GSI.

ROSE (Rotating System for 4-dimensional Emittance scans) is a rotating module for a slit-grating emittance measurement system to determine the four-dimensional transverse emittance of a particle beam as used in a linear ion accelerator or in ion sources. The four-dimensional beam emittance is the volume that an ion beam occupies in transverse phase space. Knowledge and manipulation of the emittance of the ions in the accelerator are relevant for the beam quality. Until now, the emittance has only been determined in two dimensions, separately in the two spatial directions, using two fixed measuring instruments. ROSE enables an emittance measurement that determines the coupling between the transverse planes, i.e. in four dimensions, which was previously only possible to a limited extent or not at all. The measurement is possible independently of the ion beam type, energy and intensity.

For the first time, the operating personnel of accelerator facilities are thus provided with a universally applicable measuring tool, with the help of which the settings of the existing beam guidance elements can be optimized much more efficiently.

ROSE became mobile by means of an independent electronic system for the entire ROSE system, called ROBOMAT, whose development and construction as a prototype was the central object of the project. Before the funding, ROSE was still dependent on the GSI control system and thus could not be used for other accelerators, which is why no validations could be carried out on other facilities until then. Thus, the independence of the electronics system and the development of the ROBOMAT represent the first milestone for the transfer and future distribution of ROSE.

Within the framework of the LOEWE project, after the implementation of ROBOMAT by the company Neue Technologien GmbH (NTG), ROSE with ROBOMAT was installed by GSI personnel in a test setup of the ion beam measuring facility of the Heidelberg Ion Beam Therapy Centre (HIT) in Heidelberg and the ROBOMAT was successfully put into operation outside GSI for the first time.

As a result, ROBOMAT is now available as a “stand-alone” control and data acquisition unit, which is now distributed by NTG GmbH. The result of the project, a completely independent, mobile ion beam emittance measurement system that requires only a 230V power connection, independent of the respective accelerator control system, was achieved.

The project used technical and functional details of ROSE in the patent specification of the German patent with the official grant number DE102015118017 “Drehmodul für eine Beschleunigeranlage” (rotating module for an accelerator system) and its priority claiming patent applications in Europe (Ref. EP3366090), Canada (Ref. CN108605407) and in the USA (Ref. US2018/0317310).

In February 2022, the complete system was published by the German Federal Ministry of Economics and Climate Protection as part of the WIPANO grant (Best-Practices-WIPANO/20220301).

Subsequently, the company NTG will offer “ROSE” as a complete system on the market under international licence. Forecasts predict a worldwide market share of 20% and a significant increase in sales of 250% in the field of beam diagnostics for NTG through this system.

Transfer project TUNDA++

Due to their enormous power, terawatt or petawatt laser systems can reach thresholds for ionisation of 10^{10} W/cm^2 already a few pico- or nanoseconds before the main laser pulse, be it due to poor amplified spontaneous emission (ASE) or parasitic prepulses.

To avoid these undesirable effects, one needs a way to characterise the temporal intensity profile and quality of the laser pulses with extremely high sensitivity. To achieve this, UltraFast Innovations (UFI®) and GSI have jointly developed TUNDRA++, the latest generation of UFI’s popular third-order autocorrelator TUNDRA®. TUNDRA++ is capable of measuring a dynamic range of up to 14 orders of magnitude, making it ideal for pulse contrast measurements on the world’s most powerful femtosecond laser systems. UltraFast Innovations has been distributing this licensed innovation since 2021.

Networking activities

In addition to regional and national network activities (IHK Darmstadt, "Cyber Securty Hub" - Digital City of Darmstadt, Merck, cooperation with ESA, HEAG AG, EEN Hessen, NANORA and the TTGR of the HGF), Technology Transfer is also involved in the European TT network "HEPTech" - High Energy Physics Technology Transfer Network. HEPTech was founded in 2008 as a goal of a European High Energy Particle Physics strategy and currently comprises 16 international members such as CERN, ESS or ELI. In December 2021, GSI's chairmanship of HEPTECH came to an end in accordance with the statutes, and STFC from the UK took over the chairmanship and coordination. Notwithstanding this, the successful HEPTrepreneurs digital event series continued since April 2021. So far, five episodes on relevant topics have been organized, e.g. Deep Tech Startups, Best Practice of Startups/Lighthouse Projects from the HEP field, "How Science can change the world?", Business Incubators/Startup Campus.

In November 2021, Technology Transfer participated in Tech Connect Europe - An Innovation Conference and Expo in Malmö, Sweden, with an exhibition stand, Invited Talk and a wide range of technology offerings from GSI/FAIR. The presentation included GSI/FAIR's cooperation offer to industry and was part of the Big Science Facility Summit, "Innovation in Cooperation - Industrial Access to FAIR and GSI".

In October 2021, AI STAR "Artifical Intelligence Symposium on Theory, Application& Research" was jointly organised by ESA, GSI/FAIR and Merck KGaA. The aim of this event was to promote networking in this topic between industry and academics, and was a continuation of the symposium held in February 2020 "Applied Quantum Conference".

Marketing activities of TTR: Green IT Cube / "DIGITAL OPEN LAB

The "Green IT Cube" data centre built for FAIR has six floors with the capacity of 768 19" racks in principle. The first floor, which is already fully operational, has 256 racks. Funding for the 3rd and 4th floors was recently applied for through the HMWK as part of the EU's REACT funding call and the expansion will begin in 2022. In the DIGITAL OPEN LAB, innovations for energy-efficient high-performance computing, IT R&D software projects and ultra-fast data processing will be investigated, tested and prepared for industrial application together with industry. To date, companies such as AMD, intel, Toshiba, HEAG and also Darmstadt University of Applied Sciences have expressed interest in DIGITAL OPEN LAB. A suitable contract structure is currently under discussion.

11. Research & developments for the FAIR Project

Head: Jörg Blaurock (GSI & FAIR)

Authors: Emmanuel Rosi, Mandy Raponi

Figure 87. View of the construction field as of October 2021 (GSI, D. Frentz).

The FAIR project has made good progress in all areas in 2021 and the Corona pandemic had a limited impact on the project activities on campus thanks to the measures implemented on the campus and the subcontractors on site.

A major step forward has been made in September 2021, when several shareholders confirmed their pending commitments to the FAIR budget enabling a smooth continuation of the "Intermediate Objective" of FAIR. Financing of the construction of the Modularized Start Version MSV of FAIR still needs to be clarified, and negotiations are in progress in the all shareholder countries along their own budgetary process and regulations.

On the construction site, both civil companies (construction area North and construction area South) carried out their work along the baseline schedule. A major milestone has been reached in the area North on the 20th of May 2021 by the company PORR when the ring closure of the SIS100 tunnel has been made, and the structural work has been completed. In February 2021, major contracts for the technical building installations have been awarded to six different companies. These companies will start their activities on site early 2022 following the well-coordinated preparatory work that has been performed in 2021.

Deliveries of Accelerator and Experiment components from FAIR suppliers and In-kind Partners to GSI / FAIR have continued in 2021. These components are taken into the intermediate storage in a rented warehouse facility with 9000m^2-floor area near GSI until the start of the installation activities in 2023. In line with this deadline, the Machine Installation Team has started to perform the necessary pre-assembly activities for major components arriving at GSI / FAIR in order to ensure their availability when the time of installation comes and in order to minimize the work to be performed in the tunnel and the other buildings.

Figure 88. Storage hall in Weiterstadt (Germany)

Experiments and FAIR Phase-0

The experimental collaborations continue with their preparations of the experiments. The overall progress in terms of fraction of approved TDRs, construction of experimental components and testing/commissioning is between 1 and 2% over the last 6 months. The progress in construction is slow partially due to the impact of the Covid19 pandemic and because of problems to mobilize funding for the PANDA detector in a timely manner, due the current uncertainty in the building schedule. Details can be found in the Status Report experiments. A few recent highlights and achievements are listed in the Experiments sections towards the end of this document.

11.1 Research & developments of the division SIS100/SIS18

Head: Dr. Peter Spiller (GSI)

SIS18 Status Report

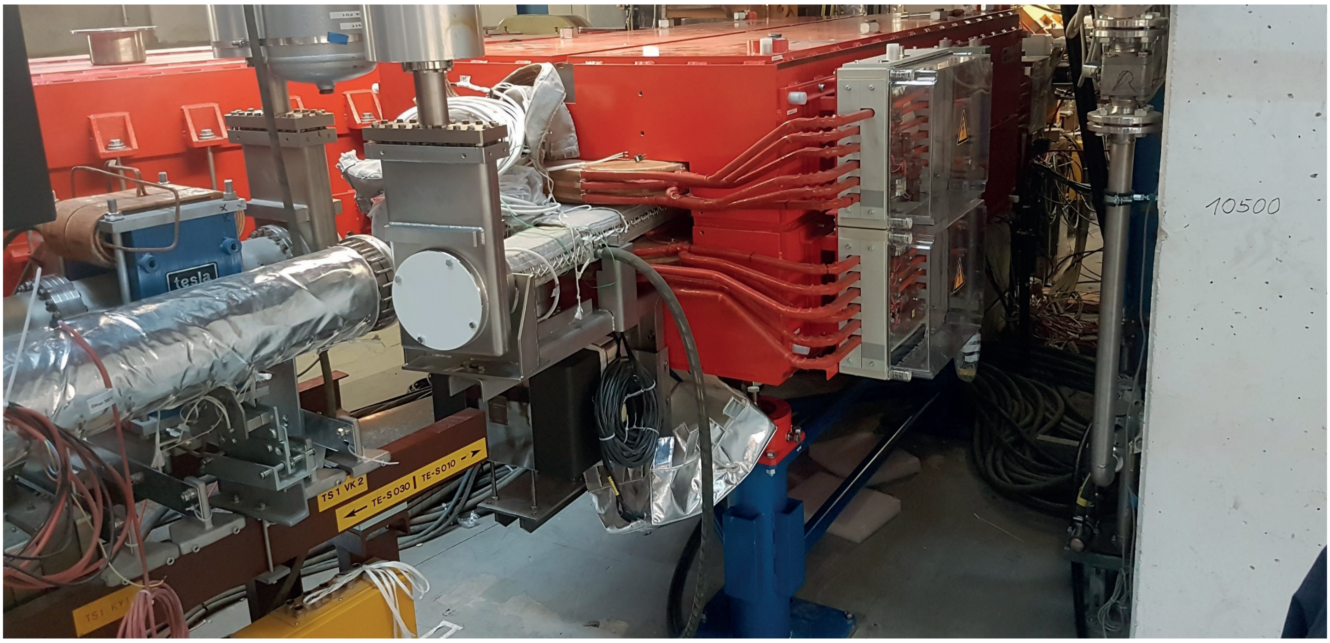


Figure 89. New bipolar dipole magnet installed in the beam line. The open flange provides the connection to the FAIR HEBT system.

A new bipolar dipole magnet, replacing the former TS1-MU1 magnet, has been installed in the TS1 beam line section behind SIS18. The magnet (Figure 89) allows to link the FAIR HEBT system to the existing beam lines on GSI campus. The magnet and its vacuum chamber are designed for fast switching between experiments on GSI campus and on the new FAIR complex.

Figure 90. Prototype cryogenic insert for the room temperature ion catcher system in SIS18.

In order to prepare for the FAIR booster operation with low charge state heavy ions, e.g. (U28+), the UHV pumping power in SIS18 has to be further increased. Therefore, the application of cryogenic inserts, providing surfaces with huge pumping power, is evaluated. In order to judge the benefit for the booster operation, the simulation performance of the STRAHLSIM code has been further improved, especially with respect to the phenomena in the cold-warms transition regions. On the other side, the pumping power and properties of prototype inserts are investigated experimentally. E.g. a matching cryogenic insert has been designed and manufactured for the existing room-temperature ion catcher system in SIS18 (Figure 90). The properties of the insert are presently studied in the laboratory. Installation and preparation for beam tests of this prototype is planned for the shut down in 2022. Furthermore, a thin-wall, ripped testing chamber has been manufactured. The chamber is equipped with a cryogenic insert to test the pumping properties on different temperature levels. Another goal is to develop a proper engineering design, e.g. for the cryogenic feed through.

SIS100 status report

Figure 91. Quadrupole module integration at Bilfinger Noell, Würzburg.

The integration process of the dipole chambers into the dipole magnets has been developed and established. The integration is supported by two external companies providing services for welding according to pressure equipment directive and UHV acceptance tests. Integration of the first half of the dipole series, comprising only the LHe cooled vacuum chamber has been completed. The series integration of the second type series, which contains also the cryo-adsorption pumps, has been launched and is advancing well. After establishing the quality standards and quality measures re-quired, the series production of quadrupole units at JINR could be launched. Twenty-four quadrupole units have been produced, cold and warm tested and shipped to company Bilfinger Noell (Germany) for integration. Following the request of Bilfinger Noell, GSI has approved advanced manufacturing of a major amount of parts for the quadrupole modules. A large number of these items has meanwhile been manufactured, accepted and stored on site of Bilfinger Noell (Figure 91).

In parallel, GSI could ensure the delivery of other major subsystems of the quadrupole modules, e.g. the cryogenic ion catchers, the thin wall quadrupole chambers and the cryogenic beam position monitors. Thus, everything relevant for the series production of modules and their integration process was prepared for the delivery of the units from JINR (Dubna, Russia). Assembly and testing of a first series quadrupole module has been finished in 2021. The delivered module has been cold tested at the GSI Series Test Facility. As with the First-of-Series module, all expected properties have been confirmed. In Salerno, the adaptation and set-up of the cryogenics facility for testing of the series of quadrupole modules has been continued. The completion has been delayed by a failure in a new transfer line. However, the commissioning is still expected for early 2022, which meets exactly the start of the module series production. In parallel, the first Missing Dipole Modules have been manufactured and delivered to GSI. In order to realize an improved safety concept, the design of the Missing Dipole Modules had to be modified and separated into two different types. The design of one module type has been changed to house additional safety valves. The demanding design of the SIS100 extraction septa has been further developed. The Lambertson septum design and specification, was the first magnet of the extraction system, ready for procurement. Meanwhile, also for the extraction septum magnets 1 and 2, the tendering process could be launched. Furthermore, the contract for the radiation hard quadrupole magnets has been awarded. The contracting of the main dipole- and quadrupole power converter was a major milestone achieved in 2021. Due to a missing external air-cooling system, a concept for an internal forced air cooling system for the bunch compression cavities had to be developed. The series production of the bypass lines has continued without unexpected events. The design of the current lead boxes has been completed. Some changes had to be implemented accounting for the large mutual forces between the bus bar systems. With the three feedboxes, the design of all local cryogenic components has been completed. Special attention has been drawn to the tight conditions at transportation in the SIS100 tunnel. Due to its large size, the transport frame of the feed boxes had to be adapted to the boundary conditions in the tunnel. As special highlight, the vacuum pipe of the SIS100 laser cooling system has been provided in time for the concrete works of the SIS100 tunnel (Figure 92).

Figure 92. The SIS100 laser cooling tube is provided for integration into the tunnel construction.

11.2 Research & developments of the division Super Fragment Separator

Head: Dr. Haik Simon (GSI)

Figure 93. Lateral iron shielding block at the FAIR site ready for installation in Super-FRS target building.

Despite the difficulties caused by the Covid-19 pandemic, the realization of the Super-FRS has progressed in R&D, design, prototyping, series production, testing and acceptance tests during the 2021. As the first work package the procurement of the lateral iron shielding of the target area could be finalized (in Jan 2022, at writing this report) and the roughly 150 iron blocks (Figure 93) with a weight of up to 25 tons each are ready for an early installation in the Super-FRS target building (expected in Q2/Q3 2022).

As an important milestone towards timely realization of Super-FRS also several contracts with in-kind partners as well as with industry could be closed in 2021. Among these are the procurement of normal conducting multipoles (Buckley Systems, New Zealand), cryo-feedboxes including jumper-systems and transferlines (WUST, Pl), the cryo-branch box as central cryo control unit and the warm-gas piping (BINP, Russia), various vacuum components covering all dipole vacuum chambers (including a special Ti-chamber for the dipoles in the target area) as well as pumping ports (BINP, Russia), quench-detection electronics (Semicon SP, Pl), beam stoppers as safety devices at final focal planes of Super-FRS (Axilon AG, Germany), the EXP DAQ which will be integral part of NUSTAR DAQ (Chalmers, Sweden), and a contract on the design of the Energy Buncher (EB) dipole magnets (CEA, France). The latter one is important since the magnet production and testing for the EB system shall directly follow the current magnet production stage and need, therefore, be prepared already by now. Although the geometric parameters of the EB dipoles are quite different from the dipoles in the separator the CEA colleagues can directly apply the design principles they developed for those magnets. For this reason, we expect a rather quick design phase and we plan to start tendering these magnets already in autumn 2022.

In 2021 we could perform altogether three beamtimes at SIS18, which lead to important results for the development of our beam instrumentation. The first two beamtimes in February and March 2021 were dedicated to the development of intensity monitors (in particular diamond detectors and ionization chamber) using Pb and U beams, respectively, at energies around 1.000 MeV/u. The results of these beamtimes allowed to conclude the CDR (Conceptual Design Review) for the so called PDC (Particle Detection Combination) which is a combination of various intensity detectors and is developed in-house. The 3rd beamtime in May used Xe beams at energies around 400 MeV/u. Here we could test together with our Finish colleagues (and in-kind partners) from Jyvaskyla their SEM Grid prototype consisting of 50 µm thick W-wires (covered by Au) with a 1 mm pitch. The detector readout was realized by a POLAND + PreAmp (APFEL) system. Also here the results allowed to conclude the CDR and in addition Finland ordered from GSI the delivery of the required POLAND systems.

Meanwhile we established regular LCM (Lean Construction Management) workshops on the major five assembly units of the Super-FRS, i.e. the super-conducting magnets, the local cryogenics, the target area, the vacuum components (including the beam instrumentation), and power converter / control racks. In the LCM workshops, the complete pre-assembly as well as the later installation in the tunnel and the supply buildings is planned in detail. In particular, we started to set-up the pre-assembly area for the super-conducting magnets which is located in the south part of the SIS18 target hall. The first super-conducting multiplet is expected to arrive at GSI in Q1 2022. After pre-assembly the heavy magnets (50 tons) will be stored in a new storage hall (BE 42) opposite to the SIS18 target hall until they can be transported to their final destination in the Super-FRS tunnel.

Also several design steps regarding civil construction and in particular the technical services were concluded. The most important was the detailed update on the required electrical power and heat losses which is available now on single-room precision. This planning includes also the definition of all major distribution systems, like cooling water, power sockets, pressurized gas, vacuum exhaust line, etc.

Superconducting magnets

Figure 94. Executing the series production of SC multiplets at ASG in La Spezia (Italy).

In 2021 the series production of SC multiplets started at company ASG, Genova/La Spezia (Italy). The Factory Acceptance Test (FAT) of five short multiplets are already concluded (Figure 94), and the FAT of several more multiplets is scheduled for Q1 and Q2 2022.

Company Elytt Energy, Bilbao, Spain, is in charge of the production of the 24 SC dipoles, of which three have a bending of 11° (type D2), 18 a bending of 9,75° (type D3), and three a special Y-form to allow the forking of the beam into two branches. In 2021, the First-Of-Series (FOS) dipoles D3 and D2 were produced. FOS-D3 was delivered to CERN for testing. With the finalization of the design of SC branched dipoles, Elytt started also the production of this type.

At the Super-FRS test facility at CERN, the test of the FOS long multiplet – consisting of 9 individual magnets – was successfully carried out. A second thermal cycle will be conducted in the beginning of 2022 in order to complete the Site Acceptance Test (SAT) of the multiplet. In parallel the qualification of the FOS D3 dipole started with corresponding warm tests. It is planned that the cold tests and magnetic measurement still start in Q1 2022 and will last few months. Since the test facility is equipped with three test benches we foresee to conduct in parallel the SAT of series multiplets.

Local cryogenics

After an already extended R&D phase we could close, as mentioned already above, the contracts with WUST (Poland) and BINP (Russia) for the overall cryogenic system. The demanding cryogenic system with an overall length of about 300m and the requirement to be able to cool 1500t of cold mass requires extensive studies and simulation calculations in order to guarantee functionality and safe operation of this extremely large distributed system. Results have been accepted for publication at the 23rd Cryogenic Engineering Conference and International Cryogenic Materials

Conference and enter the currently ongoing design activities at BINP and WUST. Indeed, it was already possible to conduct the CDR for the cryo-feedboxes (Figure 95, left) in December 2021 and the CDR of the branch box (Figure 95, right) is expected for early 2022.

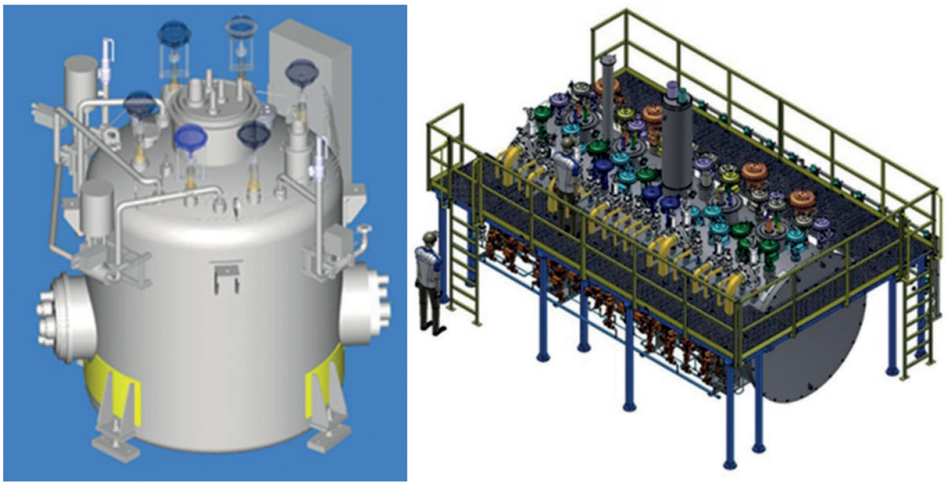


Figure 95. 3D model of the cryo feedbox (WUST, left) and the cryo branch box (BINP, right), respectively.

Target area

Remarkable progress was achieved also for other components close to the production target. The specifications for the pillow seals – a system for connecting vacuum chambers without bolts or clamps, a prerequisite for their remote operation in a hostile work environment – have been finalized and approved.

The development of a target chamber, hosting the highly radioactive rotating target with associated instrumentation for its surveillance, carried out by the former KVI-CART institute at the University of Groningen, Nederland, was completed and GSI, subsequently, could start the tendering process for the manufacturing of the chamber.

In July 2021, the Conceptual Design Review (CDR) of the Super-FRS shielding flask (Finnish in-kind contribution, provider BNG, Germany) was approved. The shielding flask system is a specialized remote maintenance and handling unit that weighs up to 52 tons and is 5.8 meters high. The shielding flask will ensure safe and secure transport of the Super-FRS highly activated beamline components (altogether 21 units) to the hot cell for maintenance. In order to benefit from obvious synergies in view of demands on both flask systems, the particular flask design was carried out in a collaborative effort with the antiproton-target subproject.

A key component for Super-FRS's operation at highest intensities are the beam catchers (or "beam dumps") which are required to catch safely the unreacted primary beam after the target together with a large share of unwanted fragments. Because of the high beam power that comes with large intensity and/or short extraction times, the direct beam must not hit the material of a normal vacuum chamber but only the dedicated absorbers mounted inside the beam catcher chambers. The design of such a demanding system, including a careful selection of materials for the catchers withstanding the heat load and shock waves has been worked out with the CMERI Durgapur, India, the material science division, the target laboratory, and several other engineering departments at GSI during the last years. The ready design is foreseen as in-kind contribution from our Indian Partners. The tender for the manufacturing of two vacuum chambers, that are required early in the installation process, has been already started with FAIR funding. The production of the remaining full system is planned to be carried out in India.

- H. Müller et al., "Superconducting magnets for Super-FRS: production and testing status", In: Proceeding of the 12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil, JACoW Publishing 2021.
- Y. Xiang et al., "Cryogenic Test of the First of Series Superconducting Short Multiplet for Super FRS at FAIR". In: 16th Cryogenics Conference, October 5-7, 2021, International Institute of Refrigeration (IIR)
- E. J. Cho et al., ""Designing and Manufacturing of the Fully Configured Multiplet for the Super-FRS at FAIR". In: MT27, 27th International Conference on Magnet Technology, November 15-19, 2021, Fukuoka, Japan
- J. Polinski et al., "Design Aspects of the Feed Boxes of the Super-FRS Local Cryogenics System". In: CEC-ICMC 21

11.3 Research & developments for the proton linac and the pbar Target

Head: Dr. Klaus Knie (GSI)

Proton Linac (pLinac)

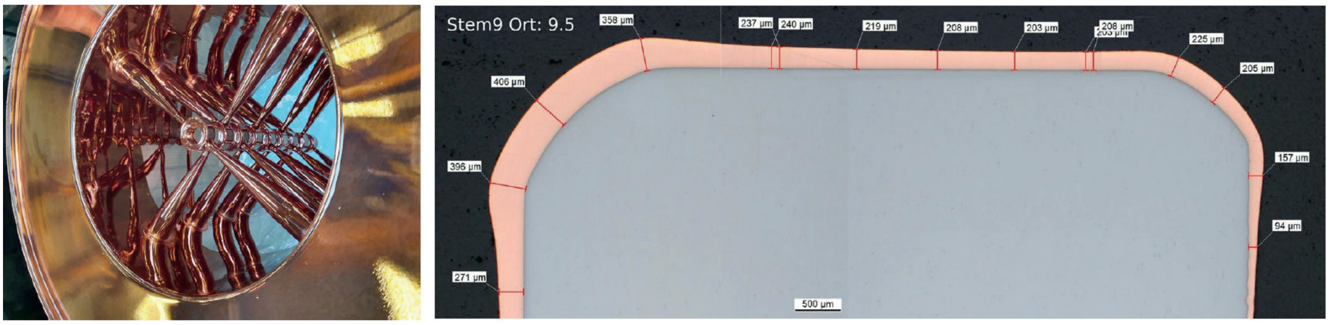


Figure 96. CH1 dummy after in-house copper plating (left) and section through a drift tube (right).

The first coupled CH (CCH) cavity (crossbar H-mode) has been contracted with an option on the other five cavities, which are needed. It is foreseen to use 3D printed stems and drift tubes in a linac cavity for the first time. As a first step, the CCH1 tank with clamped aluminum stems will be delivered this year to perform low level RF tests. In parallel, copper plating and welding test for these complex monolithic structures a progressing. Dummies of the first CH cavity were copper plated at GSI's galvanic workshop (see Figure 96). Adhesion to the base material is very good and no cracks or other defects were found in the copper layer.

The copper layer's thicknesses were measured at DEKRA. Although, the copper layer is very uniform and continuous, currently its thickness still varies too much (from 21-334 µm - required values: 40-100 µm). (see Figure 96).

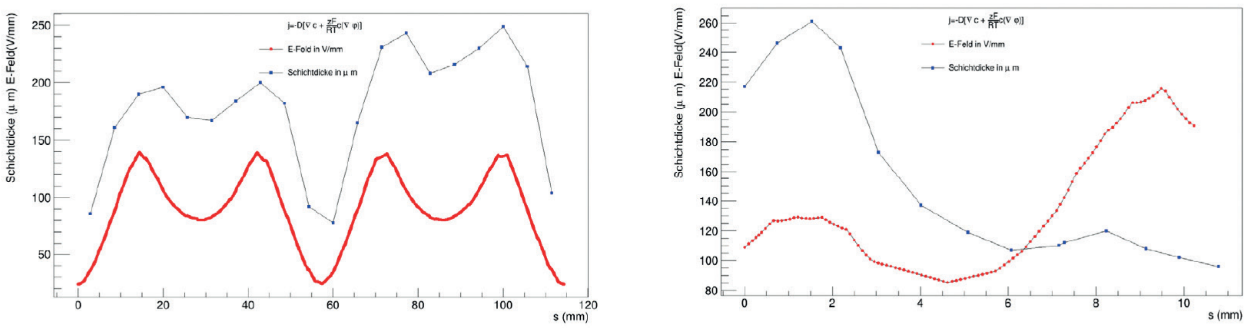


Figure 97. Measured copper layer thickness (blue) compared to simulated electrostatic field (red).

In order to obtain more information on the relevant parameters for the layer's thickness CST simulations of the electrostatic fields during copper plating have been performed in collaboration with IAP (Institut für Angewandte Physik) of the University of Frankfurt. A clear dependence of the layer thickness on the electrostatic field can be seen (see Figure 97, left plot). Therefore, an optimized geometry of the galvanic anodes should help to reduce the thickness variations. However, an additional effect due to a locally reduced copper concentration has been seen inside the drift tubes (see Figure 97, right).

The 325 MHz Feschenko Bunch Shape Monitor (BSM) was successfully put into operation and commissioned in the test beamline of the Helmholtz Linear Accelerator (cw-Linac) [1].

The FESA class for control of the Beam Position Monitors (BPM) was developed in collaboration with Cosylab (Slovenia). It could be demonstrated with delay lines and attenuators that phase and position measurements can be performed with standard algorithms provided by Cosylab as well as with customized routines. As a result of this work a basic FESA class for the BPMs is existing and was prepared to be tested during upcoming beamlines in 2022.

The major project during the year was the development and construction of the Secondary Emission Monitor (SEM) Grids for measurement of beam profile and beam emittance. In collaboration with the company Proactive (Spain) a grid could be developed which copes with the small beam diameters at the pLinac, providing high resolution due to only 0.5 mm wire distance. The design has been optimized in many respects, concerning suppression of wire cross talk and aging effects, system robustness and vacuum as well as mechanical properties have been optimized. The field distribution was optimized by extensive numerical simulations, which resulted in an elaborated design [2]. Two prototypes have been produced, which will be tested in beam operation in 2022.

The test bench for stepwise commissioning of the proton Linac will include a magnetic energy spectrometer to allow for detailed and high-resolution measurements of energy distribution behind the RFQ and the following CH drift tube accelerators. This is necessary to set the optimal rf-power and working point for each module of the linac, in particular the novel CH type structures. During the design process for this test bench, numerous particle dynamics simulations were performed to achieve an appropriate optical system for the energy measurement. At the same time the required diagnostics components where defined and assigned to the particular positions on the test bench [2].

The modulator prototype is currently being built and tested in a test setup. A first pulse at nominal voltage could be demonstrated on a test load for the first time in Q2/ 2021.

- [1] R. Singh et al. "Comparison of Feschenko BSM and Fast Faraday Cup with Low Energy Ion Beams". In: Proc. IBIC2021, WEPP1611, Pohang (online), Korea, 2021.
- [2] T. Sieber et al. " Beam diagnostics for commissioning and operation of the fair proton linac". In: Proc. IPAC2021, MOPAB315, Campinas, SP, Brazil, 2021, p. 972

Pbar target

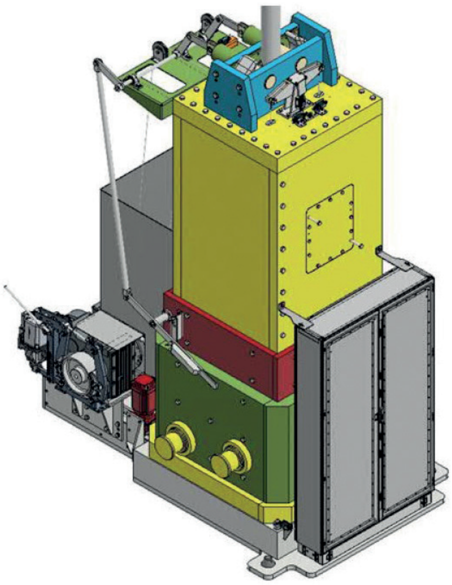


Figure 98. Conceptual design of the pbar shielding flask. Its height is approximately 4 m and its weight approximately 30 tons.

The design and production of the shielding flasks for pbar and Super-FRS for the transport of activated targets and horns to the hot cell has been started in collaboration with the company Bilfinger Noell GmbH (Germany). The Conceptual Design Review (CDR) has been accepted, the Final Design Review (FDR) is foreseen for 2022. The work on detailing the remote-controlled exchange system for highly activated components (target, magnetic horn) in the tunnel is progressing.

In 2018 an experiment was executed at the HiRadMat facility at CERN to investigate the dynamic response of different metal targets for the future antiproton target at FAIR. In order to estimate the performance of the target in the future facility, numerical simulations are carried out. The goal is to match the hydrodynamic simulations with ANSYS Autodyn with the measured surface velocity of the metal cylinders in the CERN experiment. First simulations showed that missing shock parameters for Inconel 600 prevent a sufficient accuracy of the simulations. Therefore, planar plate impact tests were performed at the Ernst-Mach-Institute (EMI) for High-Speed Dynamics. With the experimentally determined shock parameters simulations show an excellent agreement with the experimental data now.

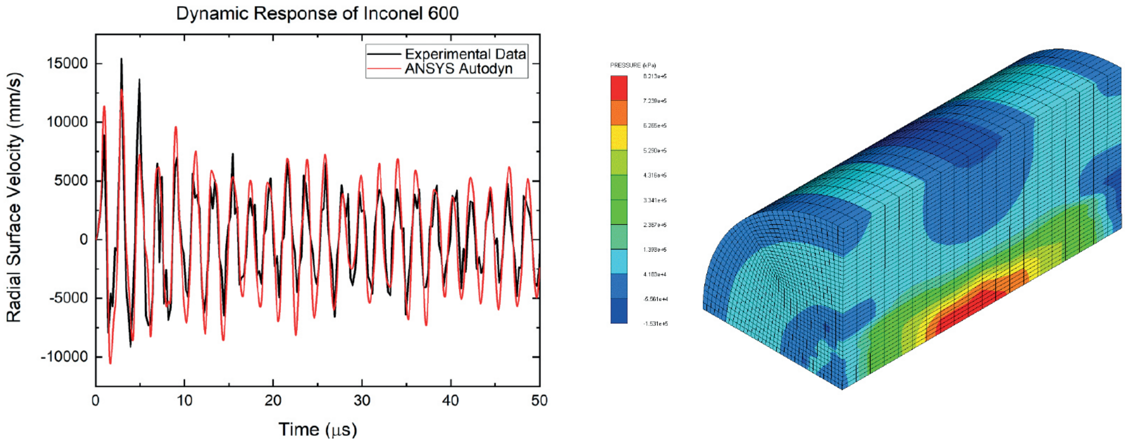


Figure 99. Dynamic Response of Inconel 600 under 440 GeV proton beam impact with an intensity of 1.6E12 ppp. Modelling in ANSYS Autodyn (after applying the parameters obtained from at EMI) and com-parison with experimental data (left). Quarter cut view of the numerical model with pressure distri-bution 20 µs after beam impact.

As main part of the pbar beam dump stainless steel plates with a total weight of about 120 tons were installed at the construction site. The whole structure was embedded with concrete inside the wall of the building 006c within construction works. Designing of an inner core of the beam dump in a form of graphite and concrete blocks combined with an additional option of cooling through a copper cooler plate was finished. Geometrical similarity between pbar, HEBT and APPA beam dumps creates a synergy opportunity for cheaper and faster purchasing and installation of graphite blocks. Combined detailed specifications were prepared and the tendering process may take place as soon as budget will be available.

Figure 100. Iron part of the pbar beamdump before it was covered with concrete.

11.4 Research & developments for the Collector Ring CR

Head: Dr. Oleksiy Dolinskyy (GSI)

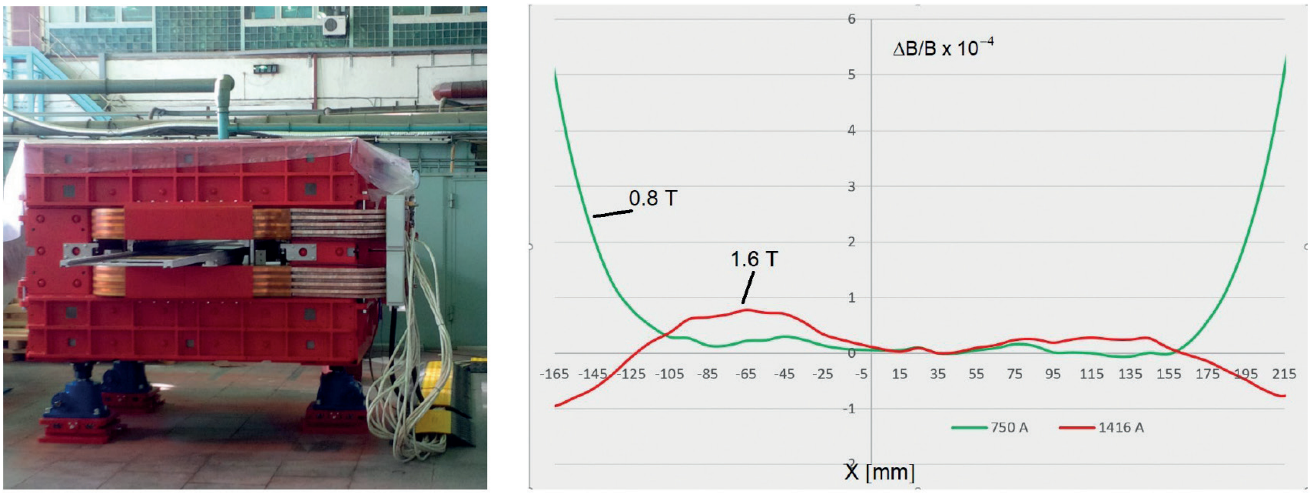


Figure 101. The CR dipole magnet (left) and measured field inhomogeneity in a median plane (right).

Production and testing of the first of series dipole magnet has been completed at BINP (Russia, Novosibirsk). The field measurements have been done using the prototype of the quadrupole power converter with the measured current stability of ±1.5 ppm at the nominal value of 1416 A. Left part of Figure 101 shows the measurement set-up consisting of an array of Hall sensors and a mechanical rail for moving the sensors through the magnet.

A Nuclear Magnetic Resonance (NMR) magnetometer has been used for calibration of the Hall probes providing the field measurement accuracy of $\pm 0.3 \cdot 10^{-6}$ in the range of 0.02 – 2.5 T. The measured integral field homogeneity at the nominal field of 1.6 T is within the range of $\pm 1 \cdot 10^{-4}$ and at 0.8 T within the range of $\pm 3 \cdot 10^{-4}$ in a specified good field region as shown in right part of Figure 101. After the FAT testing, the magnet has been disassembled and delivered in parts to FAIR. The magnet assembly and SAT testing at the GSI Target Hall is expected in Q2/ 2022.

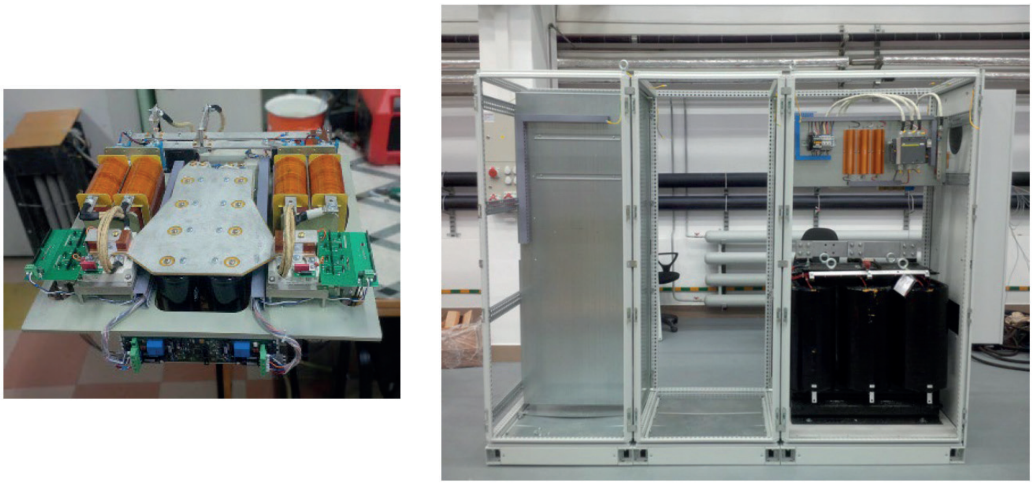
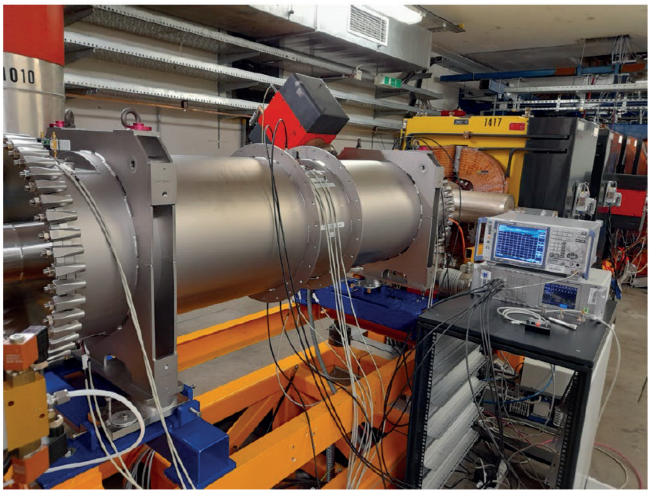


Figure 102. One 500 A power section (left) and assembly stand (right) of the quadrupole power converter prototype.

The CR quadrupole power converter (QPC) prototype is under development at BINP. The power part will consist of three 500 A sections providing the maximum current of 1500 A. In Figure 102 one power section as well as the assembly stand of the power converter are shown. After assembly and testing the power converter will be delivered to FAIR and will be used for SAT testing of the first-of-series dipole magnet.

Figure 103. Wide hexagonal chamber prototypes at BINP workshop.

Prototyping of two wide aperture hexagonal vacuum chambers has been completed after reworking and improvement of the fixation brackets of the ISO-K flange connections. The BINP will produce totally 29 hexagonal chambers of six different types to be installed into the wide quadrupole and sextupole magnets. The chambers have a wall thickness of 6 mm and a hexagonal aperture of 428 mm × 268.5 mm as shown in Figure 103. After final vacuum tests the two prototype chambers will be shipped to FAIR for integration and testing of mechanical concept of the microwave damping modules for the stochastic cooling system.



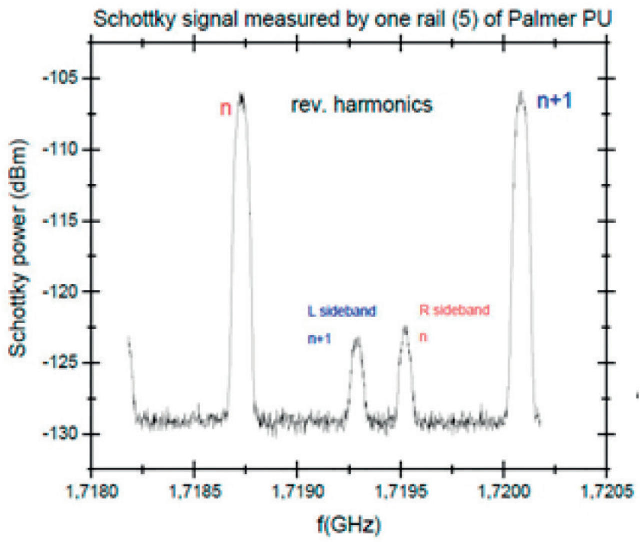


Figure 104. The stochastic cooling Palmer pick-up installed into COSY at FZ Jülich (left) and measured Schottky signal from proton beam (right).

The Palmer pick-up of the stochastic cooling system has been installed into COSY at FZ Jülich and successfully tested with beam (see Figure 104). The RF response from the Faltin rails has been measured with proton beam at the velocity of v=0.83 c and the intensity of N=1.8·1010 protons/s. Sensitivity to transverse beam position has been checked by introducing of orbit bumps to locally displace the beam and measure the Schottky power by different rails within the range of characteristic beam frequencies [1].

- [1] C. Dimopoulou et al., Update and progress report on the CR stochastic cooling system, Talk at 7th BINP-FAIR collaboration workshop, Novosibirsk, November 2021.

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

Head: Dr. Ralf Gebel (FZ Jülich)

Figure 105. Loading the first HESR quadrupole assembly for transport to Weiterstadt.

The HESR is designed to be installed with app. 200 assemblies which will be fetched from the storage hall in Weiterstadt. 45 of these assemblies have already been delivered. 67 more groups are being assembled in Jülich. Another 65 groups will be installed directly on site, 10 of them with minor assembly effort. Another group of components are the power converters. About 50 of those are already in Weiterstadt, prepared for installation. 45 further ones are in the queue for delivery to the storage hall.

Recently, the first dipole magnet for the SPARC experiment in the HESR has been delivered for storage. The assembly of these magnets is quite sensible as an extra vacuum pipe tangential to the particle beam pipe is needed for the incoming and for the outgoing laser beam. Three more magnets of that kind are still in Jülich awaiting pre-assembly.

The first quadrupole assembly was finalized and released for storage. Checking the positions of the fiducials after transport to Weiterstadt will follow during 2022.

All parts of the in-kind-contribution of Romania for the HESR (corrector magnets and their power converters) have been delivered to Jülich. 50% of these power converters could be EMC tested and released for storage. The magnets are being assembled on the respective girders and will be delivered once the individual magnet group is released for storage.

The delivery of beam position monitors to Jülich is going on continuously. All ion clearing chambers mandatory for the anti-proton operation are in Jülich now. The production of girders for the straight sections of HESR is on schedule.

The first injection kicker tank (housing two magnets) together with two pulse power converters has successfully passed the acceptance checks. It is stored in Weiterstadt. The second tank is in assembly at the manufacturer.

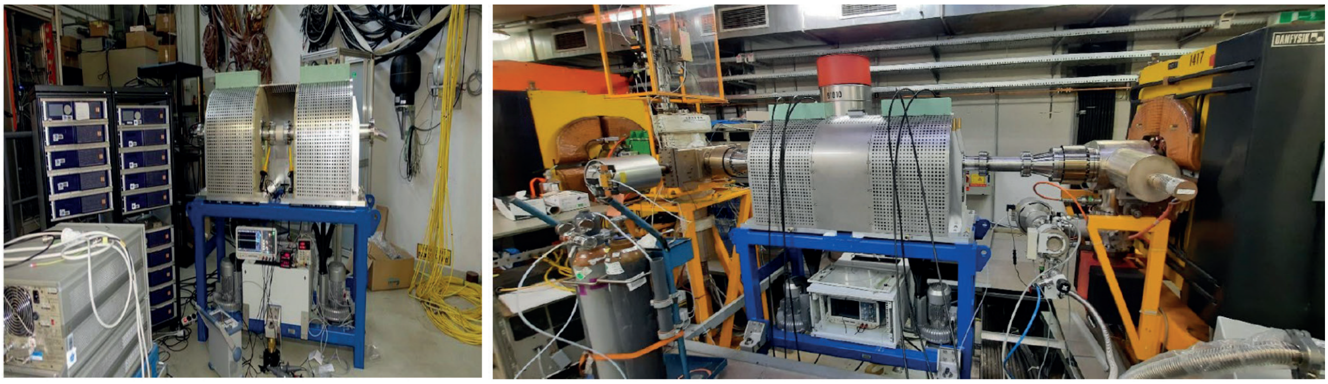


Figure 106. HESR BB cavity. Left: Cavity and solid state amplifiers during conditioning at the test bench. Right: Installed in COSY, HESR beam pipe diameter 89 mm, COSY 150 mm.

The two RF cavities for HESR have been assembled. All tests were passed successfully. One of the complete systems (air cooled cavity and solid state amplifiers) will be installed in Jülich to analyze the performance under real operating conditions.

Similarly, most relevant parts of the stochastic cooling system have been produced and one full sized system has been tested successfully at the COSY particle beams.

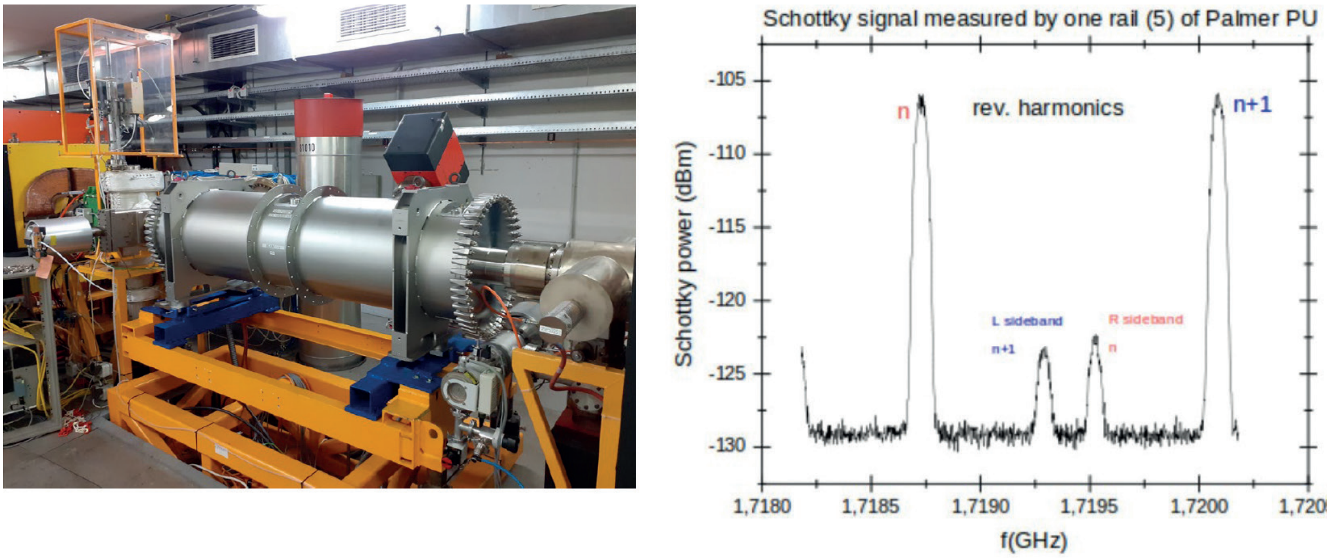


Figure 107. Left: The Palmer pick-up installed in COSY for tests with beam. Right: Typical Schottky signal measured with one of 8 rails. Coasting beam at v=0.83c, $1.8*10^{10}$ protons.

The stochastic cooling tank with the Palmer pick-up for later use in the collector ring CR was assembled in Jülich in a clean-room. The subsequent test during a dedicated beam time at COSY was successful. This was an important milestone for releasing the pick-up for FAIR usage.

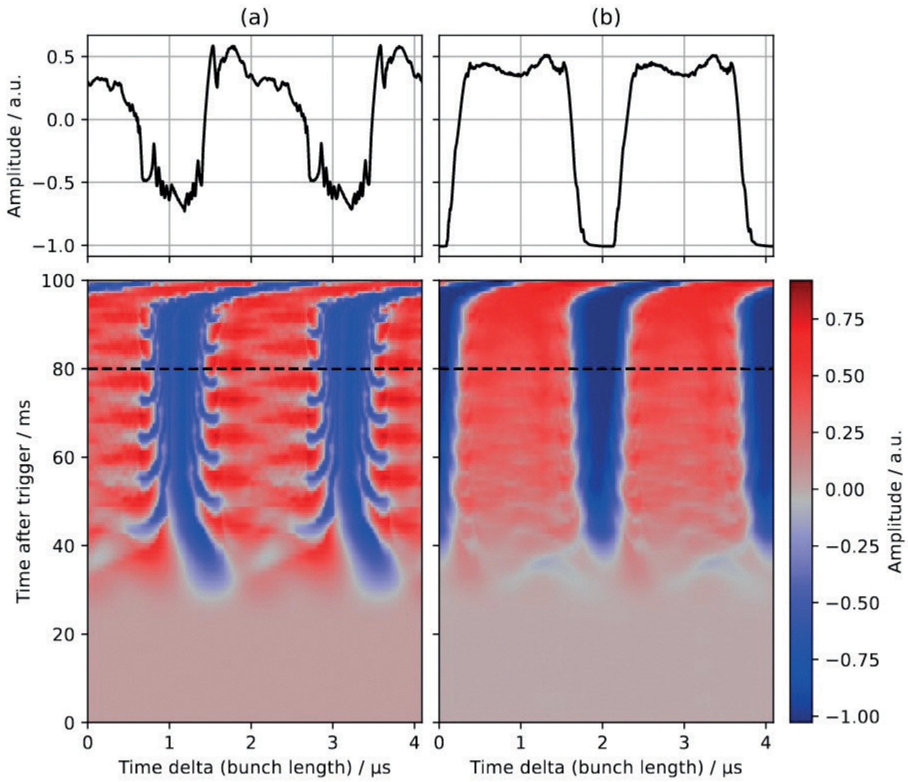


Figure 108. Bunch profiles during bunching at injection energy (a) before and (b) after the RF system was matched to the beam. The upper plots show the profiles at t = 80 ms shortly before the acceleration ramp starts. The plots show 2 consecutive turns.

A bunch shape monitor based on capacitive pick-ups hooked up to LIBERA electronics was developed and taken into operation at the Cooler Synchrotron COSY in 2021. The tool allows to monitor the evolution of the longitudinal bunch profile on a variable timescale ranging from turn-by-turn measurements up to 1 s. Thereby, transient processes like (de-)bunching can be visualized, allowing the operators to adjust and fine tune the RF system. This development and the spin-offs for more use cases are thus well established for FAIR wide usage.

11.6 Research & developments of the division Commons

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

Dept.: Beam Diagnostics (BEA)

Authors: Marcus Schwickert and Andreas Reiter

For the BEA department, the year 2021 was characterized on the one hand by a multitude of detector tests during the machine experiments and enhancements in support of FAIR Phase-0 and, on the other hand, by the continuation of the production and purchase of components for the FAIR accelerators. At UNILAC, different devices for longitudinal bunch diagnostics were installed and successfully tested, including various types of Fast Faraday Cups [BEA1], a novel non-intercepting transition radiation detector [BEA2], as well as a Feschenko-type bunch shape monitor [BEA3]. The SIS18 and ESR beam position monitor systems were substantially upgraded in order to be compatible with new FAIR standards. A novel data concentrator similar to the device planned for SIS100 was included in the SIS18 acquisition system and successfully tested. In preparation of the delivery for SIS100, the closed-orbit feedback system [BEA4] and its new frontend controller software were tested at SIS18 in collaboration with Slovenian in-kind partners.

Significant progress has been made in the GSI in-kind work package for beam diagnostic data acquisition. In the high-energy beam transport section, a novel data acquisition for resonant beam current transformers, developed in collaboration with Brazilian Synchrotron Light Source LNLS, was tested. In addition, novel ZnO-based radiation hard scintillators showed fast signal response and good stability, and were thus qualified for the usage at FAIR. New beamloss monitors will enable operation teams to localize and prevent losses more precisely. Moreover, a set of Faraday-cups in combination with a faster signal acquisition helped to improve transmission between ESR and CRYRING. Prototype development of the cryogenic current comparator for FAIR progressed well and test measurements at CRYRING yielded promising results for beam currents in the nanoampere region [BEA6]. The CRYRING ionization profile monitors were upgraded with new software offering much higher performance.

The HEBT planning was consolidated by a review of all diagnostic chambers, including pneumatic drives, detectors and vacuum components. Concerning component deliveries by in-kind partners, the first 22 diagnostic chambers of Indian provider Vacuum Techniques passed factory acceptance and are now at the beginning of 2022 on the way to FAIR. SEM-grid prototypes were manufactured by Polish provider Prevac. A first batch of the series has been delivered and accepted. While a large part of the Slovenian contribution has already been completed, the production of the pneumatic drives by Vacutech, FPGA programming by Instrumentation Technologies and software realization for beam position monitors by Cosylab continued. For beam current transformers provided by GSI, the successful resistive coating of the ceramic gap at IST, the Fraunhofer Institute for Surface Engineering and Thin Films mark the final milestone in the technical development.

- [BEA1] R. Singh et al. “Comparison of Feschenko BSM and Fast Faraday Cup with Low Energy Ion Beams”. In: Proc. IBIC2021, WEPP1611, Pohang (online), Korea, 2021.
- [BEA2] R. Singh et al. “Transition Radiation Based Diagnostics for Non-Relativistic Ion Beams”. In: Proc. IBIC2020, TUPP21, Santos (online), Brazil, 2020.
- [BEA3] S. Lauber et al. “Reconstruction of the longitudinal phase portrait for the SC CW heavy ion HELIAC at GSI”, Journal of Physics: Conference Series. 1350. 012073. 10.1088/1742-6596/1350/1/012073.
- [BEA4] S. Mirza et al. “Performance of closed orbit feedback systems with spatial model mismatch”, arXiv:2003.01693
- [BEA5] M. Saifulin et al. “Investigation of Novel Radiation Hard and Fast Scintillator for Heavy Ions Detection”. In: Proc. IBIC2020, TUAO04, Santos (online), Brazil, 2020.
- [BEA6] D. Haider et al. “Commissioning of the Cryogenic Current Comparator (CCC) at Cryring”. In: Proc. IBIC2021, WEOB02, Pohang (online), Korea, 2021.

Dept.: High Energy Beam Transport (HEB)

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

Magnets

The series production of batch1 with in total 51 dipole magnets has been completed at Efremov Institute of Electrophysical Apparatus in St. Petersburg, Russia (NIIEFA/ Russia): Eight of these magnets and five sets of spare coils arrived at GSI in 2021. As Covid-19 related travel restrictions were in power most of the year, all magnets with only one exception underwent a remote FAT procedure with NIIEFA staff. Three of the delivered magnets are already equipped with their vacuum chambers and moved to the temporary storage in Weiterstadt. The remaining magnets will undergo final testing at the NC-magnet test bench in 2022. The test bench was equipped with a new 4000A power supply in the second half of 2021 and is now operational again.

Production of the magnets of batch2&3 including all amendments (24 dipole, 181 quadrupole, 98 steering magnets) is carried out at the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia. To cope with the Covid 19 travel restrictions, TÜV auditors based in Russia were trained and sent four times for FATs to Novosibirsk. In addition, two FAT meetings with GSI staff present on site could be realized.

In 2021, one dipole dip15_1 and one dip10_0, all four quadrupoles quad10, five quadrupoles quad2 and seventeen steerers S18 were delivered. In addition, in the beginning of 2022 one dipole dip13_0, one dipole dip16_0 and ten quadrupoles quad2 arrive at GSI/FAIR. Furthermore, FATs were performed for one dipole dip10_0, nineteen quadrupoles quad2, three quadrupoles quad11, as well as twelve steerers S100 and nine steerers S18.

Power converters

The power converters for HEBT quadrupole and steering magnets will be mainly built by the Indian company ECIL (Electronics Corporation of India Limited). Up to now three contracts between FAIR, the Indian shareholder BOSE institute and the provider ECIL over in total 252 power converters for HEBT (159 for quadrupole and 93 for steering magnets) are closed. A forth contract for another six power converters for quadrupole magnets (two types) is planned to be closed in 2022.

115 power converters for quadrupoles (two types) and 48 power converters for steerers (one type) were already manufactured, successfully tested and shipped to FAIR.

The design of another 44 power converters for quadrupoles (five types) has been completed. The production of the FOS for each of these types will be finalized in the first quarter of 2022. Two FOS power converters for steerers have been successfully tested and the series production of the remaining 43 units has started. The delivery of all these power converters will be completed in the second half of 2022.

The design of 53 power converters for dipoles and eight power converters for quadrupoles was completed in 2021. The series production has started and the delivery of the first lot (27 power converters) is scheduled for Q1/Q2 2022.

Five power converters for steering magnets are planned to be contracted with Budker Institute of Nuclear Physics (BINP) in Russia.

Beam instrumentation

The status of the beam instrumentation for the High Energy Beam Transport beam lines is described in the contribution of the department for Beam Instrumentation (BEA)

Vacuum chambers

In 2021, the installation of the vacuum chambers of batch1 (51 vacuum chambers for dipole magnets, BINP) has continued in parallel with the magnet deliveries of batch 1 (from NIIEFA). In the meanwhile, 45 chambers were installed into their magnets. Completion of installation of all chambers of batch1 is expected for first half of 2022.

The Conceptual Design Review (CDR) and the Final Design Review (FDR) for all dipole, quadrupole and steerer chambers of vacuum chambers batch2&3 (BINP) has started and will be completed in the first half of 2022.

The FAT of three vacuum chambers for dipole magnets dip13 was successfully completed in November 2021. The delivery of these chambers will be in February 2022.

The Conceptual Design Review and the Final Design Review of batch 4 chambers for the first beamlines will also be completed in the first half of 2022.

The production of prototype for pumping chamber and x-cross chamber is in progress and the manufacturing of prototype for bellows is also under way for 2022.

Special installations

The first HEBT Diffusor, which is one of the constituents of the Personnel Access System of FAIR, was delivered by VA-TEC GmbH & Co KG, and tested on site in order to be fully functional. Series production can commence in Q1/2022.

The complete design of the actuators and vacuum chambers for the HEBT18 and HEBT100 beam collimation system was created in collaboration with the Mechanical Design department of GSI. Together with the detailed specifications the tender process can start in Q1/2022.

After completing the thermomechanical simulations for the HEBT beam dumps the graphite core of the beam dump in building H0705A was manufactured and delivered by CTG Carbon GmbH. Installation is planned for Q2/2022.

Special stands

The CDR for the large support frame in building H0705A was completed in April 2021. The FDR will take place in January 2022. Regarding the modular stands for HEBT, the first group of 34 frames of four different categories was awarded to Nordisk Industrioptimering AB (Sweden)/BLEICHERT AUTOMATION GmbH Co.KG (Germany) in 2021 and the CDR already completed in November. The FDR is planned for January 2022. Furthermore, the tender process for another 49 (+14 optional) frames (group 2+3) was started at the end of 2021.

Dept.: Electric Power System (EPS)

Author: Horst Welker

Machine cable management and user cable

All the user cable data continue to be maintained in the Cable DB. Latest update of cable data was provided to Fair Site & Building for the procurement process. This is in progress and the offers from the participating companies concerning the LV1 (Leistungsverzeichnis for material and laying of user cables) are expected in Q1/2022. A regular communication is established among the routing company, FSB and the cable manager. The cable routing process for the first two buildings has finished. Cable data for routing continue to be delivered. The planning of the cable trays near the machine has finished for the first two tunnels and continues for the rest.

An Expression of Interest (EOI) was introduced from the Indian in-kind partner for delivery of more cable type. Requested information and quality standards were communicated to the In-Kind partner.

Electric Power Systems (EPS)

To ensure a stable and reliable operation of the existing 900 power converters in GSI, several upgrade and refurbishment projects were realized in 2021. More precisely, the power parts of all dipole power converters for the Fragment Separator were renewed using state-of the art components and their analog control systems were upgraded to digital ones based on the FAIR standards. New high precision digital to analog converter (DAC) electronics responsible for providing the set values to the SIS18 main power converters were developed, installed and successfully tested during the beam time in 2021. In parallel, the old Programmable Logic Controller (PLC) systems of these power converters were exchanged by modern Siemens S7 systems. Additionally, a part of the input supply switchgears was exchanged in order to increase the availability and safety of the systems. The 200kV isolation transformers of the ion sources, the dipole power converter of the PIG ion source and the power converter for the new FAIR switching magnet TS1MU1 were installed and tested.

A 2500A power converter was installed at the Direct Current Current Transformer (DCCT) laboratory to calibrate up to seven DCCT systems at the same time. For calibration of DCCTs with nominal currents above 2500A, a high precision 5A reference current source was developed, supplying the calibration windings of the DCCTs.

Dept.: Cryogenics (CRY)

Author: 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. However, the department supports also small consumers like the HED collaboration in setting up the final focusing system and the large-scale experiments CBM / HADES and Panda.

Furthermore, the department is responsible for the so-called local cryogenics of 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 50.000 h of operation. All 110 SIS100 dipole magnets and all 18 SIS100 current lead pairs were tested so far. In 2021, SIS100 quadrupole modules have been testing and the assembly of a string set-up was started. Additionally, the missing dipole modules have been also tested.

Procurement of the FAIR cryo plant CRYO2 (German GSI In-kind)

The central Cryo plant for FAIR CRY02 will provide the helium cooling capacity for SIS100, Super-FRS, CBM and HADES. It comprises a 14 kW @ 4 K and 50 kW @ 50 – 80 K cryo plant, connected to a campus wide 1.6 km long distribution system. Concerning the Super-FRS, a dedicated Cool-down and Warm-up Unit (CWU) was specified in order to realize a reasonable cool-down and warm-up time from ambient temperature to around 90 K. CRYO2 and CWU were ordered in one lot together with the distribution box DB3. The last final design review (FDR-3) was accepted in December 2021. The compressor skits have been produced already and the installation is planned to start in June 2022, followed by the commissioning in 2023.

Cryogenic distribution system

The Cryogenic Distribution System is divided into three major lots: the SIS100 distribution system, the north/ south transfer line including DB2 supplying also CBM / HADES and the SuperFRS distribution system. For the SIS100 distribution system except of the DB4 all parts are produced in 2021, stored and ready for installation beginning in Mai 2022. In 2022, the rest of the FAIR cryogenic distribution system will be procured.

CRYRING cooling

In 2021, the CRYRING electron cooler solenoid was cooled continuously during 6 months of beam time. Securing the beam time, a failure of the recovery compressor was repaired within one week, resulting in a moderate loss of helium only.

Dept.: Accelerator Controls System (ACO)

Author: Ralph Bär

The accelerator control system for FAIR including the GSI injectors are continued to be designed and developed as In-kind contribution of the GSI Controls group with contributions by the Slovenian Technodrom consortium. Fully consistent with the overall development and implementation strategy of the FAIR control system, focus is still on the implementation, testing and commissioning of the future system at the existing GSI injector chain (SIS18, CRYRING, GSI-HEBT) for FAIR Phase 0.

Since the complete replacement of the old GSI accelerator control system by the FAIR control system in 2016-2018, the new system has been successfully operated in three regular beam times in 2019 till 2021. This allows to execute a rich experimental physics program 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 2021 were concentrated on further improving system performance in order to reduce the operational system response and latency time, while changes of settings and trims are carried out. With additional improvements on all layers of the control system, the system performance was substantially enhanced for the physics beam time 2021 in order to allow an efficient machine setting and trimming by the operation and machine experts' team.

Thus a basic version of the FAIR control system is in use and in operation for the FAIR Phase-0 beam times already today, years 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. Nevertheless, some minor technical and performance limits and in individual controls subcomponents have already been identified during commissioning and operation, requiring some technical revisions or re-designs of these subsystems. However, these issues are identified early enough in the FAIR project to mitigate and none are considered critical from technical or project schedule execution point of view.

Moreover, significant progress has been made in 2021 on all control system subprojects. Highlights are:

- Extensive cross-system improvements and modifications on all layers of the control systems were done to implement the SIS18 booster mode, allowing for fast repetition synchrotron cycles to support the FAIR injector mode into the SIS100.
- The FAIR bunch-to-bucket (B2B) synchronization and injection system was further developed and successfully tested at SIS18 and ESR in machine experiments. These works required extensive works at the accelerator timing system, the RF- and fast magnetic kicker control. Based on excellent results, exceeding the design parameters, this system was implemented for regular beam operation for the beam time 2022.
- •Further development and appliance of the fundamental underlying control system software frameworks for accelerator equipment control (FESA), communication middleware, databases, as well on user interfaces graphical control room applications.

Dept.: Vacuum Systems (VAC)

Author: Andreas Krämer

The department VAC is responsible for the operation of the vacuum systems of the GSI accelerator facility and for the design and realization of large parts of the vacuum systems for the FAIR project. For these purpose, VAC operates a vacuum laboratory where vacuum acceptance tests of components to be installed either at GSI or FAIR are conducted. In 2021, about 100 vacuum chambers and components were tested, this includes ea. SIS100 dipole chamber, SIS100 standard pumping chambers, HEBT beam diagnostic chambers, SIS100 & HEBT BPMs and components for experiments in ESR & CRYRING. In addition, VAC supports the Accelerator Operation Division in service, reconstruction and upgrade of accelerator components during the shutdown 2021 and for preparing the planned beam time program.

In the frame work of the FAIR project, the specification and procurement of standard vacuum components like vacuum pumps have been continued. Here the contracts for the delivery of ion getter pumps with company Agilent Technologies and for NEG pumps with company SAES Getters SpA were signed. Also a contract for delivery of vacuum gauge of type Extractor with company Leybold GmbH was closed.

12. Annex

All publications of the GSI in the year 2021 and all publications related to GSI's large scale research facilities are listed in the publications database (VDB) at the GSI repository.

12.1 GSI and FAIR committees in the years 2021

Ingo Augustin, FAIR; Karin Füssel, GSI

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Prof. Dr. Cornelia Denz, Westfälische Wilhelms-Universität Münster (Germany)

Prof. Dr. Thomas Glasmacher, Facility for Rare Isotope Beams, East Lansing (USA)

Prof. Dr. Thomas Nilsson, Chalmers University of Technology, Göteborg (Sweden) as Vice-Chair of the Joint Scientific Council GSI/FAIR

Dr. Bettina Lommel, GSI Helmholtzzentrum für Schwerionenforschung, as spokesperson of the Scientific-Technical Council of GSI

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Prof. Dr. Victor Yu. Egorychev, NRC Kurchatov Institute, as representative of the Russian Federation

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Prof. Dr. Sibaji Raha, Bose Institute, as representative of India

Katri Huitu, Helsinki Institute of Physics

Niklas Ottosson, Swedish Research Council (Vetenkapsrådet), as representatives of the Swedish/Finnish Consortium

Dr. Cornelia Anca Ghinescu, Ministry of Research and Innovation, as representative of Romania

Dr. Ruxandra Popescu, Ministry of Research and Innovation, as representative of Romania

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Dr. Mateusz Gczyński, Department of Innovation and Development of the Ministry of Science and High Education, as representative of Poland

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Dr. Fanny Farget, Centre National de la Recherche Scientifique (CNRS), as representative of the French shareholder CNRS

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Dr. Andrej Kugler, Nuclear Physics Institute of the Czech Academy of Sciences, as representative of the Czech Republic

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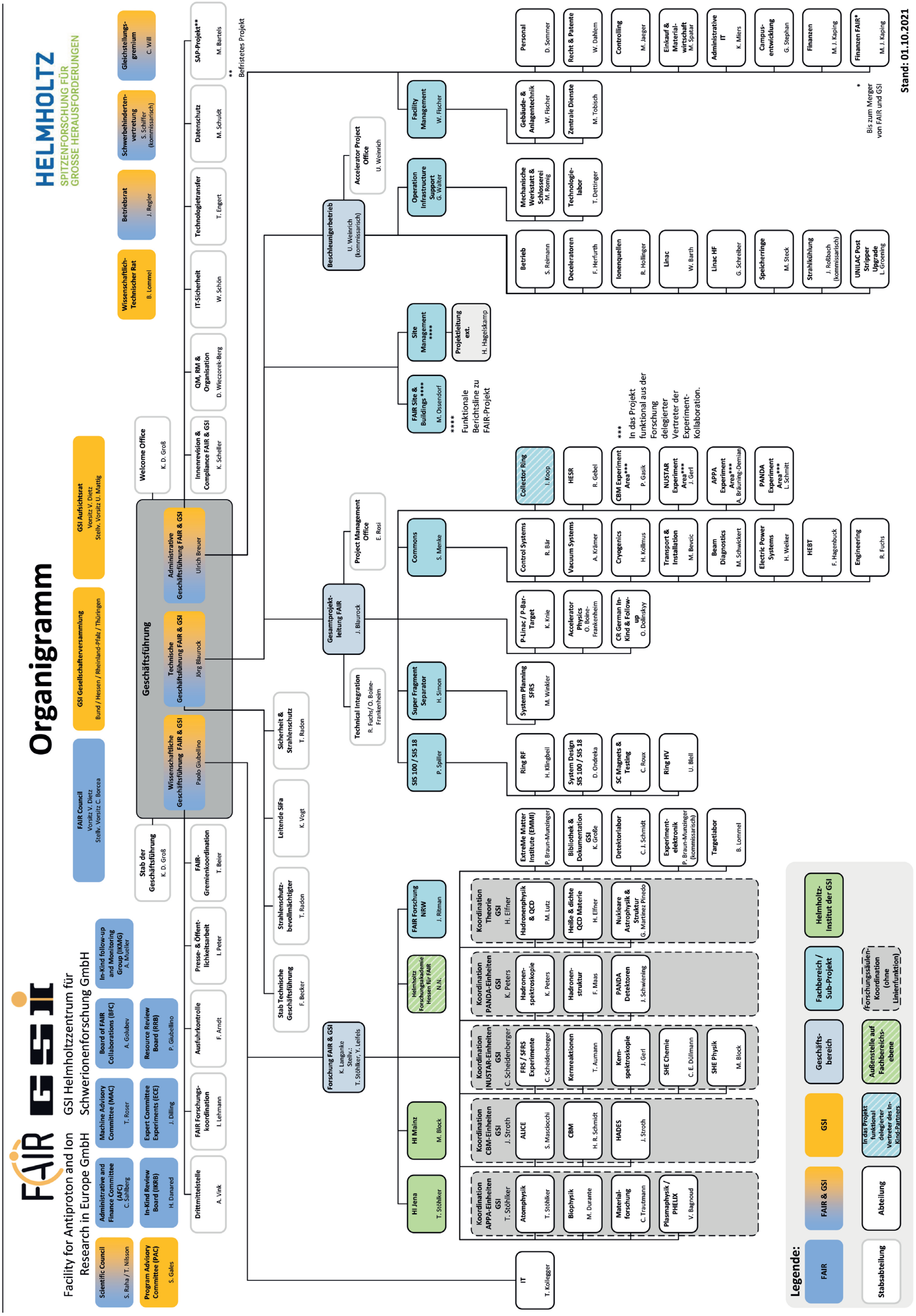
Scienctific Secretary: Karin Füssel

12.2 Organisational chart



GSI is a member of the largest national non-university science organization, the Hermann von Helmholtz Association of German Research Centers (e.V.), in the contributions to solve big and pressing questions of society, science and economy in a total of six research areas: energy, earth and environment, health, key technologies, matter, traffic and space. GSI is researching in the research field of matter of the program-oriented research of the Helmholtz Association. At the GSI, basic research is applied, but also application-oriented esearch in the disciplines of hadron and nuclear physics, nuclear astrophysics, atomic physics, plasma physics, materials research as well as biophysics, radiation biology, space research, and medical technology.

GSI Helmholtz-Zentrum für Schwerionenforschung GmbH operates a worldwide unique one accelerator system for ion beams with adjoining experimental equipment. The purpose of GSI is to promote science and research, in particular through the development, construction and operation of accelerator systems for Hadron and ion beams as well as basic and applied research on the areas of science, materials science, and life sciences. For the future sees GSI the realization and use of the Facility for Antiproton and Ion Research (FAIR) in international cooperation as the most urgent goal. Partners of GSI are the Federal Republic of Germany with 90%, the country Hesse with 8%, the Free State of Thuringia with 1% and the Land Rhineland-Palatinate with 1% shares. The Helmholtz institutes in Jena and Mainz become 90% external branches of GSI funded by the federal government and 10% by Thuringia and Rhineland-Palatinate. On behalf of the Federal Ministry of Education and Research (BMBF), the GSI is German Shareholder of the Facility for Antiproton and Ion Research in Europe, founded in 2010 GmbH (FAIR GmbH), in cooperation with nine partner countries - Germany, Finland, France, India, Poland, Romania, Russia, Sweden, and Slovenia - as well as the United Kingdom as associated partner - first the construction and later the operation of the FAIR plant in Darmstadt is tracked.