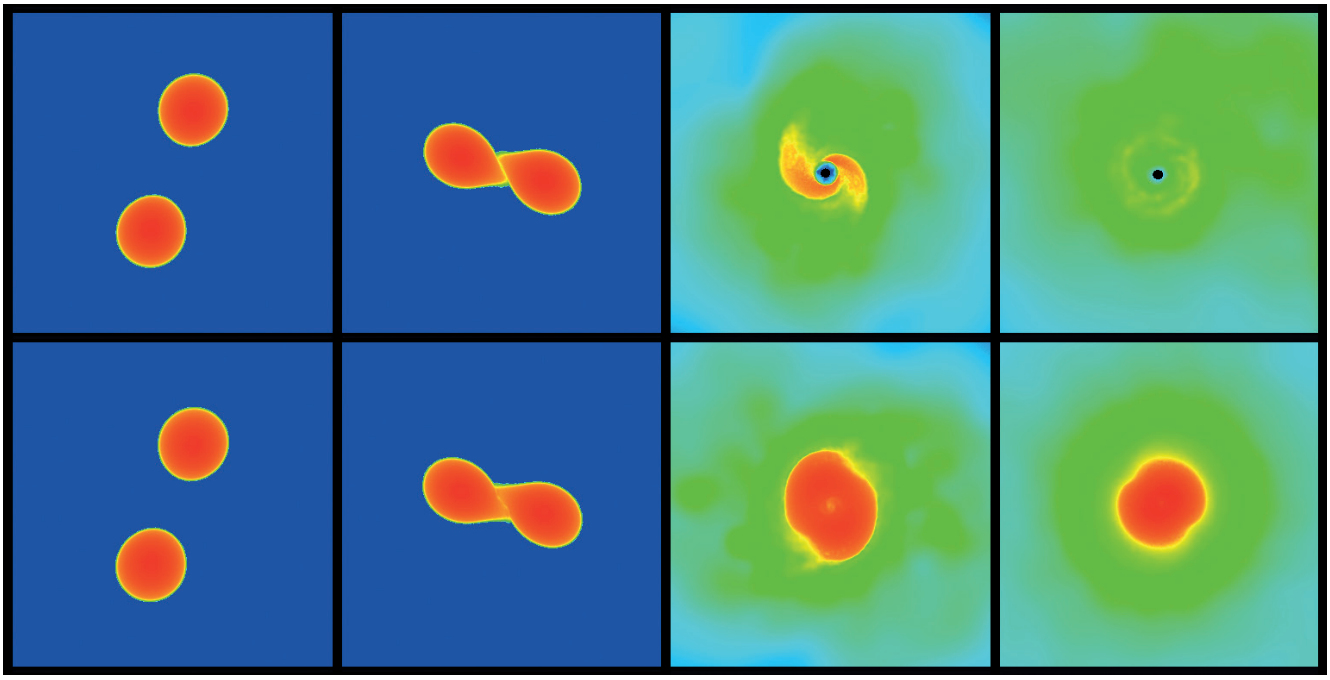
GSI REPORT 2021-1

GSI-FAIR SCIENTIFIC REPORT 2020

An overview of the 2020 achievements in science and technology



FAIR Phase-0 Research Program

GSI FAIR

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Cover

Neutron stars are the remnants of massive stars, which explode as supernovae. The collision of two neutron stars in a binary system can either lead to the formation of a black hole (upper panels) or it can form a massive rotating neutron star remnant (lower panels). The outcome depends on the total mass of the system in comparison to the threshold mass for black-hole formation. The merger product has dramatic consequences for the observable signals of a neutron star collision. For instance, telescopes can observe electromagnetic emission, which is powered by the radioactive decays of nuclei produced by the rapid neutron-capture process in the ejecta, or instruments like Advanced LIGO and Virgo detect gravitational radiation from the merger. A GSI team in collaboration with researchers from Wroclaw, Thessaloniki, New York and Atlanta has performed computer simulations of neutron star mergers to understand the conditions for black-hole formation in these systems and to determine the threshold mass for gravitational collapse, which can be considered as an upper limit for the mass of cold neutron stars. By studying these dependencies, current and future observations of neutron star mergers can be employed to learn about the properties of high-density matter and the nucleosynthesis of heavy elements, which links this theoretical investigation to experiments at GSI and FAIR. See also page 78.

By A. Bauswein/GSI

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Phase-0
Research Program

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Imprint

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Contents

1. Executive summary of the research at GSI & FAIR

Coordination: Prof. Dr. Karlheinz Langanke, Technische Universität Darmstadt & GSI
Authors: Dr. Yvonne Leifels, GSI

Executive Summary

The main focus of the research division was the design and construction of the FAIR detectors and the preparation of the FAIR Phase-0 experiments. The beam time period started in February just after the strategic evaluation of the programme Matter took place in January 2020 in Berlin.

The beam time was overshadowed by the outbreak of COVID-19. However, it was possible to perform a substantial number of experiments due to the enthusiasm and the dedication of the operation crew of the accelerators and the local personnel of the research division with the valuable help of numerous external collaborators, which contributed to the preparation of the experiments in person but participated more often only remotely to the beam time.

The beam time 2020 came to an end June 7th after three months of experiments and an engineering run, during which crucial tests of the accelerator performance were carried out. Despite all the restrictions due to the Corona pandemic, e.g. no travel for external collaborators, more difficult working conditions due to social distancing and lacking man power due to home office for persons at risks, it was possible to continue operation and perform approximately 2/3 of the experimental shifts, which were originally scheduled.

The FAIR Phase-0 programme has attracted considerable attention, recently. The European Research Council (ERC) awarded three of the prestigious ERC Advanced Grants to researchers with close ties to the FAIR Phase-0 programme, namely:

- Prof. Marco Durante (GSI and TU-Darmstadt, Germany) plans to develop novel techniques in tumour treatment with charged particle and to study new opportunities utilizing radioactive ion beams in FAIR Phase-0;
- Prof. Gabriel Martínez-Pinedo (GSI and TU-Darmstadt, Germany) intends to further progress the understanding of the r-process nucleosynthesis, which is and will be studied from the experimental side in FAIR Phase-0 and the future FAIR facility;
- and in addition, Prof. Beatriz Jurado (Centre Etudes Nucléaires de Bordeaux Gradignan, CENBG, France) will exploit the CRYRING storage ring at GSI/FAIR to investigate nuclear reactions of astrophysical relevance.

Those awards show the international recognition of the science performed at FAIR and will help to help to strengthen the scientific programme and attract the scientific community to FAIR already during Phase-0.

Also, scientists linked to GSI have received prestigious prizes: Friedrich-Karl Thielemann, emeritus professor from the University of Basel and now guest scientist at GSI, received the Karl Schwarzschild Medal. The Horst Klein Award for outstanding achievements in the field of accelerator physics was awarded to Bernhard Franzke, a former plus leading accelerator physicist at GSI. Jan Rothard, HI-Jena, received the Röntgen Award 2020 of the University of Gießen.

Strategic Evaluation for the next POF IV funding period

The strategic evaluation of the HGF Research Field Matter took place January 27 - 29, 2020, in Berlin. The eleven-member evaluation committee was headed by Ursula Bassler, Research Director of CNRS, and evaluated the strategic proposals of the different topics along four categories: Goals, Workplan, Competences and Resources, Impact and Risks.

An overview of the research programmes and topics within Matter is shown below. The research field is divided into three programmes (“Matter and the Universe, MU”, “Matter and Technologies, MT” and “Matter to Materials and Life, MML”), nine research topics (LKI) and seven facility topics (LKII). GSI contributes to all three programmes.

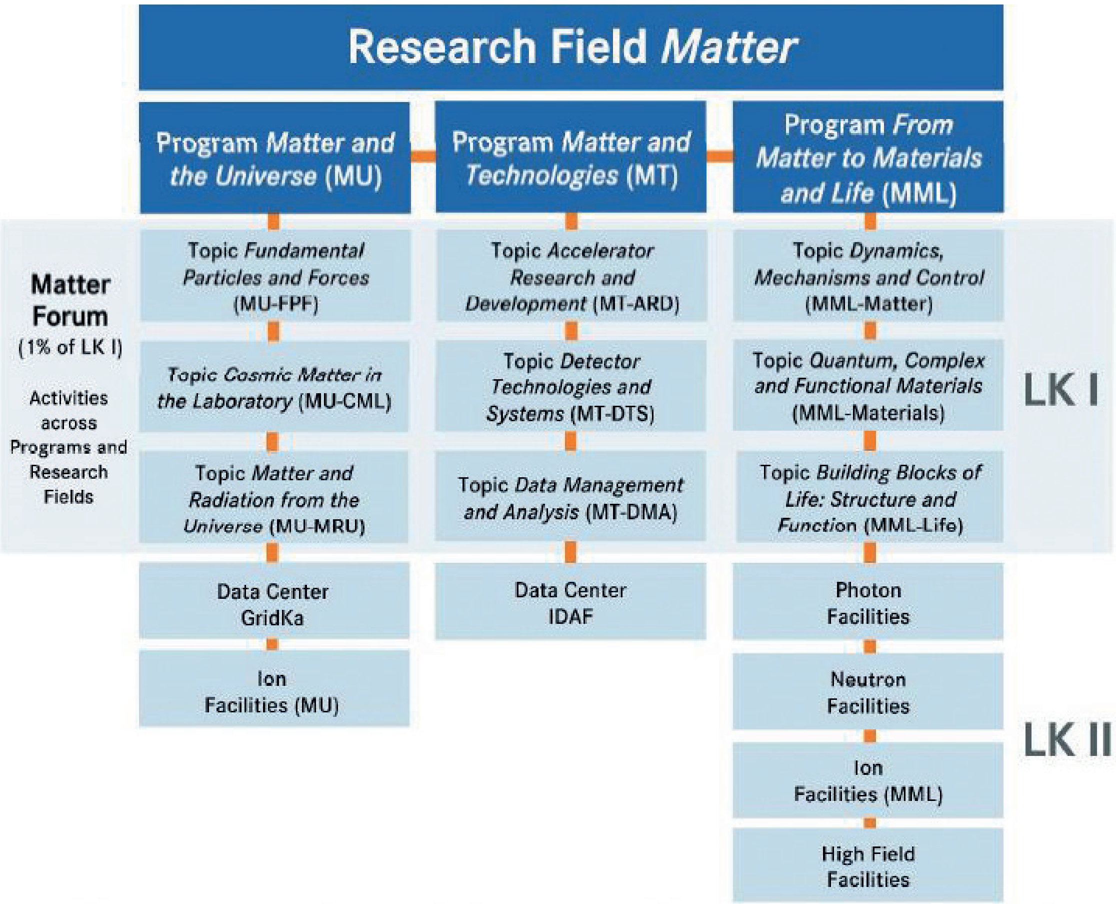


Figure 1. Overview on the Research Field Matter with its three programmes. Overview on the Research Field Matter with its three programmes.

GSI was well represented among the programme and topic speakers by the head of the Atomic physics department and director of the Helmholtz Institute Jena, Th. Stöhlker (spokesperson MML), C. Fournier, scientists of the Biophysics department (spokesperson of the topic Life in MML), E. Toimil Morales from Materials science (spokesperson of the facility topic Ion Facilties in MML), F. Maas from the Helmholtz Institute Mainz, and T. Galatyuk from HADES (spokesperson and deputy spokesperson of Cosmic Matter in the Laboratory in MU), Y. Leifels and M. Block from the Super Heavy Elements group (spokesperson and deputy spokesperson of the facility topic Ion Facilities in MU) and S. Masciocchi head of ALICE at GSI (deputy spokesperson of the topic DTS in MT).

As decided by the Supervisory Board, GSI participates only partially to the POF programme focusing on research within FAIR Phase-0.

In the programme MU with its three research topics, GSI was represented only in the topic Cosmic Matter in the Laboratory, CML. The topic CML was rated with “Outstanding” for both categories “Goals” and “Competence and Resources”. The presented “Work Programme” has been rated as “Excellent”. “Impact and Risks” have been rated “Very Good”. The committee argued, “...that in 3 months of beam time per year, there is little possibility of obtaining results comparable to those of the most highly rated topics.”. Despite the very positive evaluation of the other categories the topic was rated only “C” in relation to the others.

In the programme MML, GSI scientists contribute to all three topics of the research programme. The topic Life, in which the GSI Biophysics department, which was previously in the Research Field Health, contributes substantially, was assigned the top grade “A”. The other topics where also evaluated as “Outstanding” and “Excellent” and were rated with the overall grade “B”.

In the programme Matter and Technologies, MT there are three topics “Accelerator Research and Development, ARD”, “Detector Technologies and Systems, DTS” and “Data Management and Analysis, DMA”. GSI is participating in all three of them. Here, ARD was rated “A” and the others received the grade “B”.

Except for the rating “Very good” in the “Impact and Risk” category in CML due to the limited length of the beam time which can be provided by the GSI accelerators during FAIR Phase-0, but not due to the quality of research, all our grades have been either “Outstanding” or “Excellent”. This confirms the scientific potential and the technological competences and the quality of people involved on this campus.

FAIR Phase-0 beam time

The FAIR Phase-0 beam period started as planned in February 2020. In November/December 2019 an engineering run took place, in which already interesting results have been achieved. The most important milestone achieved in the 2020 beam time period is the operation of the main accelerators, SIS18, fragment separator FRS, the storage rings ESR and CRYRING@ESR with the new accelerator control system; in particular, it was possible to inject a beam, which was cooled and decelerated, into CRYRING. During this beam time period the full accelerator chain including FRS, ESR and CRYRING is finally operational.

The first experiments took place still largely unaffected by the travel restrictions, which have been imposed by authorities in response to the ongoing pandemic of COVID-19. These restrictions prevented external collaborators to travel to the beam times and the experiments were progressively performed by relying on expertise and work force of the local personnel with only remote involvement of external collaboration members.

Beam delivery for experiments was continued under specific and strict safety measures, which were implemented to counter the spread of the COVID-19. Parallel operation, i.e. serving more than one experiment at the accelerators, has been limited in order to ease the workload on the operating crew.

Despite these general conditions, a considerable number of experiments were completed. Major milestones are the first storage-ring experiments, which have been performed successfully with the new FAIR control system in place at ESR and CRYRING.

Experiments, which rely heavily on external collaboration members and equipment, could not be carried out under the COVID-19 restriction. However, 2/3 of the envisaged scientific programme could successfully be completed during this beam period, as the operation conditions ensuring the safety of all involved could be maintained.

To further adapt to the situation, it was decided to postpone the meeting of the General Programme Advisory Committee (G-PAC) from June to August, such that the outcome of this campaign and the expectations for the next campaign could be taken into account as much as possible.

In addition, GSI/FAIR uses its research potential and unique infrastructure to contribute to research on the current COVID-19 Pandemic. GSI/FAIR Scientists are working to provide new insights and technologies that may help to fight the corona virus SARS-CoV-2. To this aim, the accelerators and laboratories on the Darmstadt campus are also being used.

Four projects are currently being developed to exploit the possibilities of GSI and FAIR research in the COVID-19 Pandemic and to expand the fundamental knowledge about the virus. The researchers are working on contributions to the development of vaccines as well as on therapeutic low-dose irradiation options for pneumonia caused by SARS-CoV-2. Other projects aim at the development of faster and optimised virus detection and at the possibility of producing improved viral filtration masks.

Program Advisory Committees in 2020

G-PAC

The 44th meeting of the G-PAC took place from August, 26th to 28th as a video meeting. The overall interest in the meeting was quite high, with at times more than 100 persons attending the open video session. The G-PAC was preceded by a call for proposals, which was open until June 10th, and which was addressed to beamtime in the years 2021 and 2022. A total of 95 proposals covering all scientific topics of GSI have been submitted to the G-PAC (173 proposals in total for all PACs). In the 95 proposals, 3.215 shifts of beam time (a shift is defined 8 hours, i.e. there are three shifts per day) have been requested. Not only the number of proposals made this call a success, but also their high quality.

The G-PAC could allocate 265 shifts for UNILAC experiments, 341 shifts for SIS18/FRS experiments, and 369 shifts for ESR, CRYRING and HITRAP experiments ("Quota"). The resulting overbooking is quite large compared to previous calls, in the peak a factor of 5 for SIS18/FRS experiments. Therefore, the SIS18 beam time was extended and 80 more shifts were attributed to the G-PAC resulting in 421 shifts which were distributed to SIS18/FRS experiments. Nevertheless, the evaluation of the proposals was a demanding task for the G-PAC members.

MAT-PAC

The 4th meeting of the GSI Materials Science Program Advisory Committee (Mat-PAC) was held on June 16/17, 2020. The members of the Mat-PAC were connected by video. In total 31 experiment proposals were submitted with a total request of beamtime of 396,4 shifts. The total request contains of 287,6 shifts at UNILAC, 76,6 shifts at SIS and 32,2 shifts at CRYRING. For Materials Research 143 shifts of UNILAC-, 31 shifts of SIS- and 25 shifts of CRYRING-beamtime are available, which gives a factor of 2-3 of overbooking. The committee was impressed by the quality and the focus of the proposals submitted to the Mat-PAC. The community submitting the proposals is very broad and the spokespersons of the proposals come from seven different countries.

Bio-PAC

Despite the pandemic, biophysics has a very small backlog of experiments (10 out of 12 experiments implemented). The new Bio-PAC has seen a tremendous increase in the number of proposals, 25 have been submitted, (+125% compared to the previous call) and 133.5 shifts have been requested (+73%), a clear success of the Biophysics Collaboration that has worked hard in 2019 to coordinate the European efforts in biomedical applications at accelerators.

Beamtime in 2020

Coordinator: Dr. Daniel Severin

experiment proposal number	spokesperson	large scale facility and target station	experiment topic	main shifts	parasitic shifts
E129	Rothardt, Jan	CRYRING	Photoionization of C^+ ions at CRYRING	10	
E135	Winters, Danyal	ESR	Laser spectroscopy of the (1s2 2s2p) $^3P_0$ - $^3P_1$ level splitting in Be-like krypton	12	
E132	Hagmann, Siegbert	ESR	Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions	47	
E121	Litvinov, Yuri	FRS-ESR	Measurement of the bound-state beta decay of bare ^{205}Tl ions	31	
E127	Reifarth, Rene	FRS-ESR	Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process	16	
S471	Herrmann, Norbert	SIS18 mCBM	mCBM @ SIS18 - A CBM full system test-setup for high-rate nucleus-nucleus collisions at GSI / FAIR	17	4
S477	Stroth, Joachim	SIS18 HAD	Properties of hadron resonances and baryon rich matter	5	
S444	Gernhäuser, Roman	SIS18 HTC	R3B - 2018 commissioning (CALIFA, L3T, GLAD, NeuLAND & Tracking)	17	
S467	Paschalis, Stefanos	SIS18 HTC	Single-particle structure of neutron-rich Ca isotopes: shell evolution along Z=20	17	
S443, S459, S472	Mukha, Ivan; Mardor, Israel; Chudoba, Vrastislav	SIS18 FRS	Four-proton radioactivity of ^{18}Mg; Two-proton radioactivity of unobserved ^{26}S; A Novel Method for Measuring beta-Delayed Neutron Emission	7	
S457	Itahashi, Kenta	SIS18 FRS	Search for η' -mesic nuclei in ^{12}C(p,dp) reaction	6	
S474	Plass, Wolfang	SIS18 FRS	Detector tests with the prototype of the Cryogenic Stoppping Cell for the Super-FRS and direct mass measurements of neutron-deficient nuclides below 100Sn	17	
S468	Pietri, Stefan	SIS18 FRS	Search for new neutron-rich isotopes and exploratory studies in the element range from terbium to rhenium	33	

S469	Purushothaman, Sivaji	SIS18 FRS	Accurate slowing-down measurements of heavy ions in gases and solids in the kinetic energy range of (30 to 300) MeV/u with the high-resolution magnetic spectrometer FRS	11	
S482	Hornung, Christine	SIS18 FRS	Mean range bunching for experiments with stopped beams	8	
S451	Katrick, Peter	SIS18	Depth profiling of activity induced by lost heavy ions		2
S480	Regan, Patrick	SIS18	Seniority transitions and electormagnetic transition rates in ^{94}Pd	17	
S481	Witt, Waldemar	SIS18	Proposal to collect implantation and decay data with the AIDA active implanter	6	
U308	Yakushev, Alexander	UNILAC X8	First chemical study of element 113 behind TASCA	79	16
U310	Rudolph, Dirk	UNILAC X8	Spectroscopy of flerovium decay chains & discovery of ^{290}Fl	38	
U312	Block, Michael	UNILAC Y7	Direct mass measurements and investigations of isomeric states in Lr and Rf isotopes around the deformed neutron shell closure at N = 152 with SHIPTRAP	22	7
U313	Laatiaoui, Mustapha	UNILAC Y7	Laser spectroscopy of nobelium and lawrencium	70	
UBIO		UNILAC X6	Various experiments	0	8
SBIO		SIS18 HTA	Various experiments	16	
ESA		SIS18 HTA	Various experiments	13	
UMAT		UNILAC M1-M3, X0	Various experiments	28	79
SMAT		SIS18 HTA	Various experiments	13	12
U317	Rozmej, Olga	UNILAC Z7– PHELIX	X-ray mapping of the heavy ion beam intensity distribution and the ion beam energy loss in the plasma physics experiments at FAIR		7

Table 1. Beamtime in 2020

2. Research of the APPA departments

Coordination: Prof. Dr. Thomas Stöhlker, GSI, Helmholtz-Institut Jena & Friedrich-Schiller-Universität Jena
Author: Prof. Dr. Thomas Stöhlker

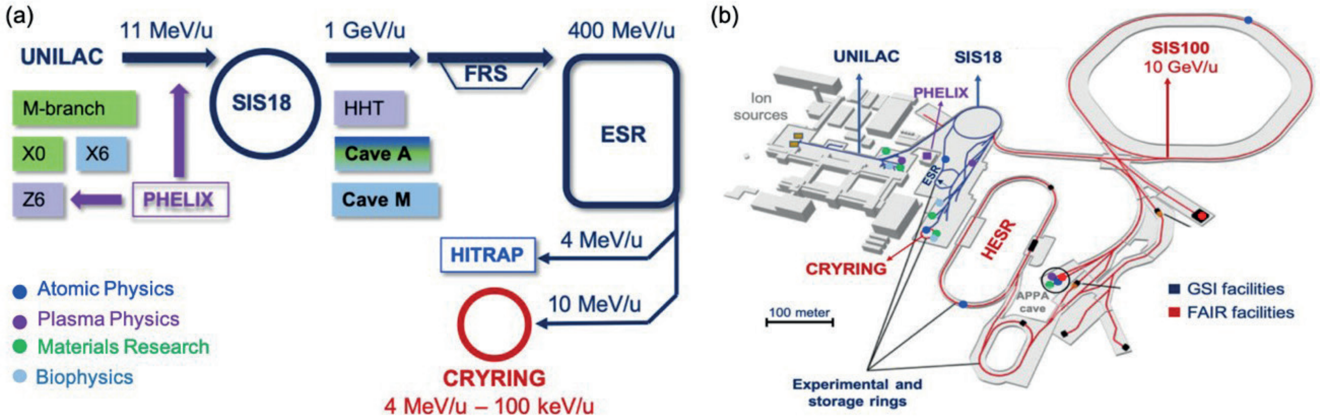


Figure 2. (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (For more Information to APPA at FAIR see Th. Stöhlker et al., Nucl. Instr.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

At GSI, the research departments Atomic Physics, Biophysics, Plasma Physics, and Materials Research are organized under the roof of APPA/MML, where MML is the Helmholtz program “From Matter to Materials and Life”, and APPA, “Atomic, Plasma Physics and Application”, is one of the four research pillars of FAIR. With the intense ion beams, GSI and in particular 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 programs 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 2 depicts an overview of experimental stations devoted to MML/APPA physics at GSI and the future FAIR facility.

2.1 Department Atomic Physics

Head: Prof. Dr. Thomas Stöhlker, GSI, Helmholtz-Institut Jena & Friedrich-Schiller-Universität Jena
Authors: A. Bräuning-Demian, S. Bernitt, J. Glorius, A. Gumberidze, S. Hagmann, F. Herfurth, P.-M. Hillebrand, M. Lestinsky, Y. Litvinov, E. Menz, W. Quint, U. Spillmann, G. Weber, and T. Stöhlker

Figure 3. From September 14th to 17th, the SPARC Collaboration held its 17th Topical Workshop and Collaboration Meeting online (in the figure, a snapshot of participants during a session is displayed). More than 160 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. The particular focus of the workshop was on the very first experiments scheduled for FAIR Phase-0 at ESR and CRYRING@ESR.

In close cooperation with scientists from all over the world, and especially within the framework of the SPARC collaboration (see Figure 3), part of the APPA research pillar at FAIR, the working groups of the 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 (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. In order to reach its research goals, particular important activities of the AP division are related to the development and implementation of novel, state of the art instrumentation (such as e.g. internal targets, electron spectrocopy, lasers, x- and γ-ray polarimeters, cryogenic micro-calorimetric detectors for soft and hard x-rays, and Schottky devices). Instrumentation and detection concepts are permanently under scrutiny and in case adjusted, to enabled optimal use of the above-mentioned research infrastructures.

In 2020, emphasis was given to the very first storage ring experiments at the ESR after a long interruption period of several years as well as on experiments at the just implemented CRYRING@ ESR (a Swedish in-kind contribution to FAIR). Delayed by more than two years in spring 2020 and despite COVID-19, it was possible to bring the ESR back to operation and to perform first successful experiments. Also, CRYRING@ESR appears now fully operational and the storage and cooling of high-Z ions at highest charge state was accomplished. This is more than encouraging news for the midterm perspectives for SPARC related research at GSI/FAIR. These achievements were only possible due to extraordinary engagement of the various local GSI teams (e.g. ESR team, CRYRING team, and the members of the atomic physics department). But we like to emphasize in addition the important role of our external partners. For sure, it must have been a hard time for our colleagues, having prepared these experiments but finally being unable to attend. Special thanks to all of you having contributed to the very successful commissioning and beam time campaign in 2020.

In the following we concentrate on the research achievements of the Atomic Physics department/ SPARC collaboration obtained within the framework of FAIR Phase-0 (and before), comprising experiments conducted at GSI but also at external facilities (CERN, DESY).

Note, for all 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.

Highlights in 2020

Experiments at the storage ring CRYRING@ESR

Figure 4. View of the CRYRING

During 2020, CRYRING@ESR (see Figure 4) 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, and the observed lifetimes of the beams of highly charged ions (Pb^{79+} and Pb^{82+}) lie within the predicted range. Independent operation of CRYRING with beam delivered through a local injector beamline was improved with the implementation of a compact Electron Cyclotron Resonance ECR-type source contributed by colleagues from Gießen and adapted to the HV ion source terminal of the injector and integrated to the FAIR-type control system. As a significant upgrade from the previous MINIS-type ion source, the ECR increases the beam intensity and gives access to higher charge states.

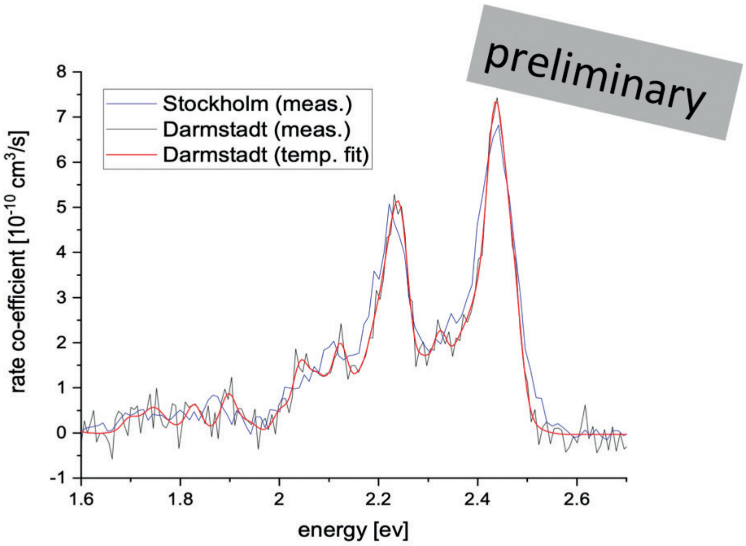


Figure 5. Analysis of Ne^{7+} DR (Dielectronic Recombination) data taken with CRYRING's ultra-cold electron cooler during the spring run is fulfilling expectations, the electron beam temperatures are in agreement with prior performance of the cooler at Stockholm. The figure to the right compares previous Stockholm data (Boehm et al., 2005) with data obtained in Darmstadt. The fit is based on theory by Lindroth (1999) and convoluted with electron temperatures of $k_BT_{\parallel}$ = 0.05 meV and $k_BT_{\perp}$ = 2.6 meV, which are in the range expected for the beam conditions used.

During machine test runs in December, beam extraction and a novel cryogenic current comparator (allowing absolute beam intensity measurements down to approximately 5nA) were successfully commissioned.

Beams stored in 2020: d^+, Mg^+, Pb^{78+}, Pb^{82+}, Ne^{7+}, Ne3+, and Ne^{4+}.

First Observation of X-Ray Emission from H-like High-Z Ions at CRYRING@ESR Electron Cooler

Pb^{82+} ions provided by the ESR at an energy of 10 MeV/u were injected into the CRYRING and allowed for a commissioning of the E138 experiment (1s Lamb Shift in H-like Uranium), as the beam lifetimes, ion trajectories and x-ray energies are expected to be quite similar as for U^{92+}. Even though in this very first beam time with bare heavy ions in CRYRING only a low intensity of max. $2*10^5$ ions per injection was achieved, a few days of continuous operation were sufficient to accumulate meaningful spectral information when combining the signals in both x-ray detectors with the particle detector, see figure below.

At the electron cooler, equipped with dedicated chambers for housing of the view ports for x-ray detection equipped with thin Be windows, standard high-purity germanium x-ray detectors were mounted at exactly 0° and 180° observation angles. An ion detector was successfully operated downstream to the cooler, enabling to record x-rays associated with recombination in the electron cooler section. In the figure below, a corresponding x-ray spectrum associated with radiative recombination as observed at 0-deg is depicted. Beside the Lyman and K-RR transitions, in particular relevant for the 1s Lamb shift study, intense Balmer and even Paschen radiation can be identified. Since most of these transitions are basically unaffected by QED corrections, they may provide a unique means for an intrinsic Doppler correction in future studies.

This first x-ray test experiment with bare high-Z ions documents considerable progress towards future precision x-ray studies at CRYRING@ESR (see Figure 6). For the upcoming E138 experiment of the 1s Lamb Shift Collaboration at CRYRING@ESR, a substantial increase of the number of stored ions as well as further improvements of the ring vacuum to about 10^{-11} mbar are mandatory. Moreover, the experiment relies on the application of high resolution cryogenic micro-calorimeters currently being prepared at the University of Heidelberg.

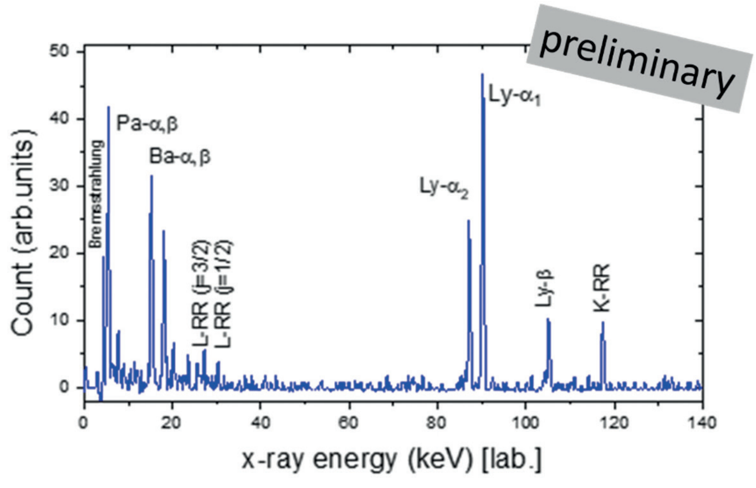


Figure 6. Preliminary x-ray spectrum associated with radiative recombination, observed at the 0-deg view port at the CRYRING@ESR electron cooler.

Experiments at the storage ring ESR

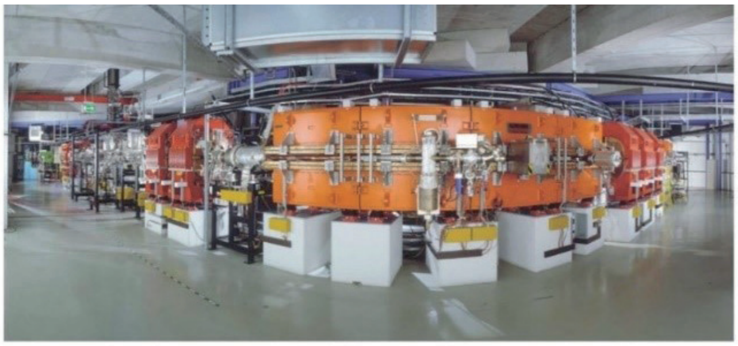


Figure 7. View of the ESR.

Although significantly affected by 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. Indeed, many of these items could first be accomplished within setting up of physics experiments which sometimes caused unexpected complications. Two from three experiments, which could take the beam in 2020, have been completed. Brief reports are given below. COVID-19 related restrictions led to a cancellation of several experiments, which enabled extended beam to commission the extraction of slowed-down beams towards CRYRING@ESR (see Figure 4). Remaining issues are the isochronous ion-optical mode and extraction towards HITRAP, which will be addressed in the coming year. The re-established versatile experimental capabilities are reflected in 24 proposals at the ESR or involving ESR to the last GPAC. All these would not be possible without the motivated and hard work of the ESR team which we greatly appreciate.

E121 Bound-state beta decay of $^{205}Tl^{81+}$ ions

The experiment, which has been first proposed in late 1980s, was finally accomplished in Spring 2020. ^{205}Tl is stable as neutral atom and is present on Earth. However, if all bound electrons are removed, an exotic bound-state beta decay becomes energetically possible. In an ordinary beta-minus decay one of the neutrons in the nucleus is transmuted to a proton with an emission of electron and electron antineutrino. In the bound-state decay, the electron is not emitted to continuum but occupies one of the free atomic orbitals thus saving the binding energy. By measuring the bound state beta decay of ^{205}Tl, the constraints on the origin of the matter of our solar system will be made. Furthermore, neutrino capture cross section on ^{205}Tl to the first excited state in ^{205}Pb will be deduced.

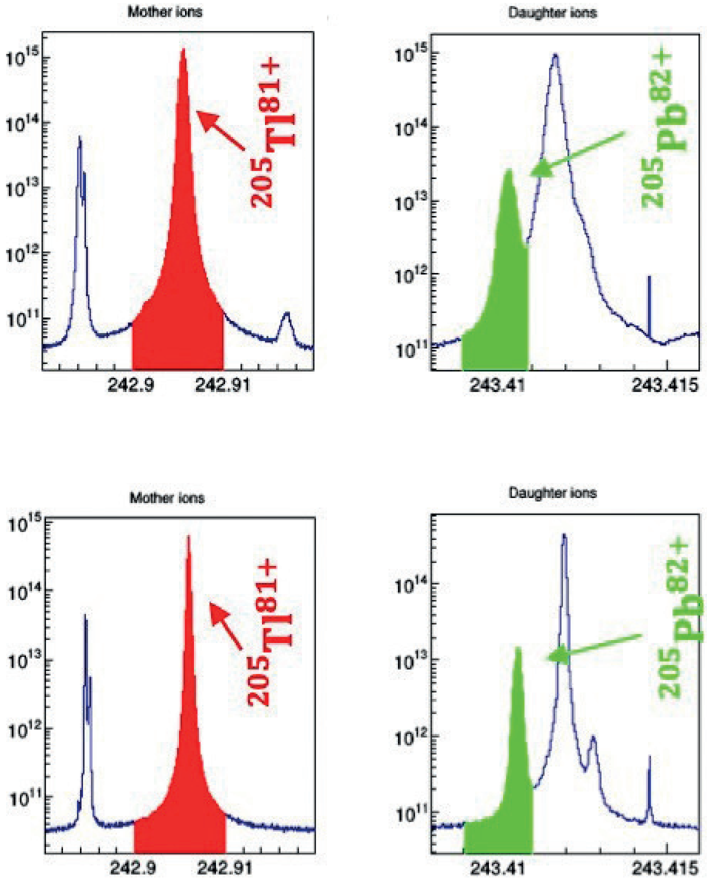


Figure 8. Schottky spectra of parent $^{205}Tl^{81+}$ (Left) and daughter $^{205}Pb^{82+}$ (Right) ions measured in the ESR right after the accumulation (Top) and after 10 hours waiting time (Bottom).

Beam of $^{205}Tl^{81+}$ was produced in the Fragment Separator FRS (see Figure 8). The first challenge was to remove the strong contamination by $^{205}Pb^{81+}$ ions, which are the daughter ions of the decay of interest. By employing energy degrader, a high purity of $^{205}Tl^{81+}$ beam could be achieved. The expected half-life is in the order of one year and a high intensity is required in the ESR, which is the next challenge. Therefore, several tens of injections of the ions into the ESR were accumulated reaching an average beam intensity of a few 10^6 ions. Afterwards, the electron current was reduced to minimum to enable longest possible storage times and the beam was left undisturbed for several, up to 10, hours to decay. The last challenge was to count the number of produced several ten $^{205}Pb^{81+}$ daughter ions, which are hidden inside the intense $^{205}Tl^{81+}$ beam. For this purpose, Ar internal target was operated for 10 minutes to strip the bound electron from Pb ions, which were then seen either in a dedicated detector or directly in Schottky frequency spectra. The experimental data are being presently analyzed.

E127 Proton-capture rates for nuclear astrophysics

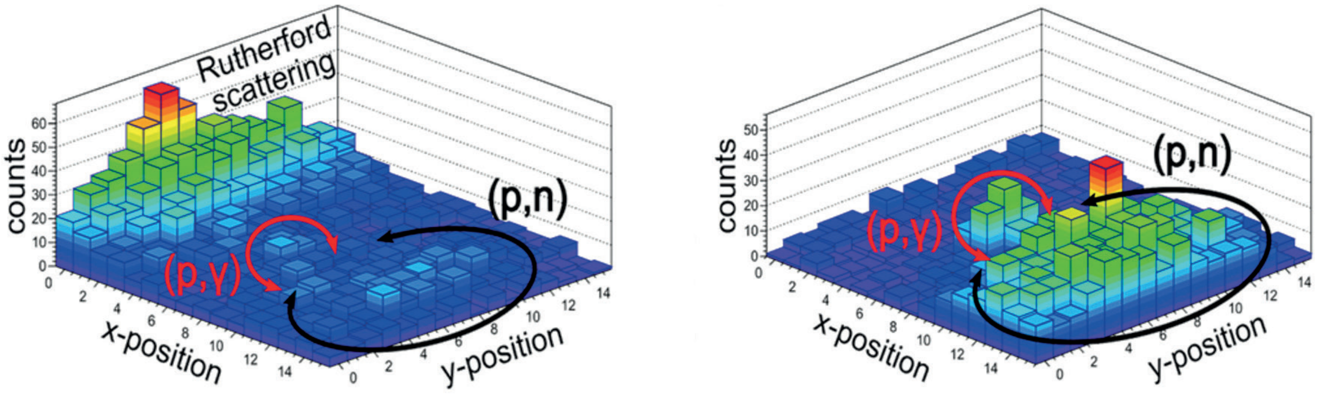


Figure 9. Distributions of ion hits on the double-sided silicon-strip detector installed inside the dipole magnet of the ESR downstream the hydrogen internal target. (Left) Dominant contribution due to Rutherford scattering is clearly seen, which is efficiently and selectively removed (Right) by a dedicated scraper installed before the dipole magnet.

Previously, a successful measurement of the proton capture reaction on stable ^{124}Xe in the center-of-mass energy range from 6 to 8 MeV/u could be conducted in the ESR. The lowest energy is just at the upper end of the Gamow window of the p-process of stellar explosive nucleosynthesis. However, the major goal is to perform such reactions on radioactive ions and at even lower energies, as will be available in CRYRING@ESR. The first proof-of-principle experiment on radioactive ions has been attempted in Spring 2020. The chosen ion was ^{118}Te, which was produced and separated in the Fragment Separator FRS. The beam was injected into the ESR at 400 A MeV energy to enable quick stochastic cooling of the very “hot” secondary beam after nuclear reaction (see Figure 9). Unfortunately, slowing down to lowest energies turned out to be technically impossible. It was the hardware issue which was realized first during the experiment. However, several conceptual tests could be performed at the lowest accessible energy of 10 A MeV. It could undoubtedly be shown that the major source of background due to elastic scattering of the hydrogen internal target is efficiently removed by a dedicated scraper installed in front of the dipole downstream the target.

E131 Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions

The 1sσ molecular orbital and the evolution of its energy in very heavy quasimolecular collision systems have been in the focus of experimental and theoretical endeavors since the prediction of its diving into the Dirac sea for transient supercritical systems with $Z_{UA} \geq 173$. Previous studies of adiabatic collisions were limited to either medium-charged heavy projectiles or highly-charged, medium-heavy projectiles. Only the ESR provides the unique possibility to let decelerated bare heavy-ions at low energies collide with heavy target gases. Due to the huge atomic cross sections in these collision systems, one major key to success is a very low but stable target density in order to achieve a decent beam lifetime in the ring and single-collision conditions.

In a successful beam time in spring 2020, we investigated symmetric collisions of bare, H-like, and He-like xenon projectiles with a Xe target, at 30 and 15 MeV/u. Here, the Bohr-velocity of the K-shell is 1.6 and 2.2 times higher than the collision velocity, respectively, which illustrates the strongly perturbative character of the collision systems. Our observables were emitted x-rays, up- and down-charged projectile ions, emitted cusp electrons, and target recoil ions. Special emphasis was given to the single and double target K-shell vacancy production, which is the characteristic signature for the evolution of the 1sσ molecular orbital in the quasi-molecular collision. Here, we aim to probe the theoretical fully-relativistic time-dependent two-center calculations performed by our colleagues in St. Petersburg. A preliminary x-ray spectrum is shown in the Figure 10. The data analysis and the preparation of the publication is presently ongoing.

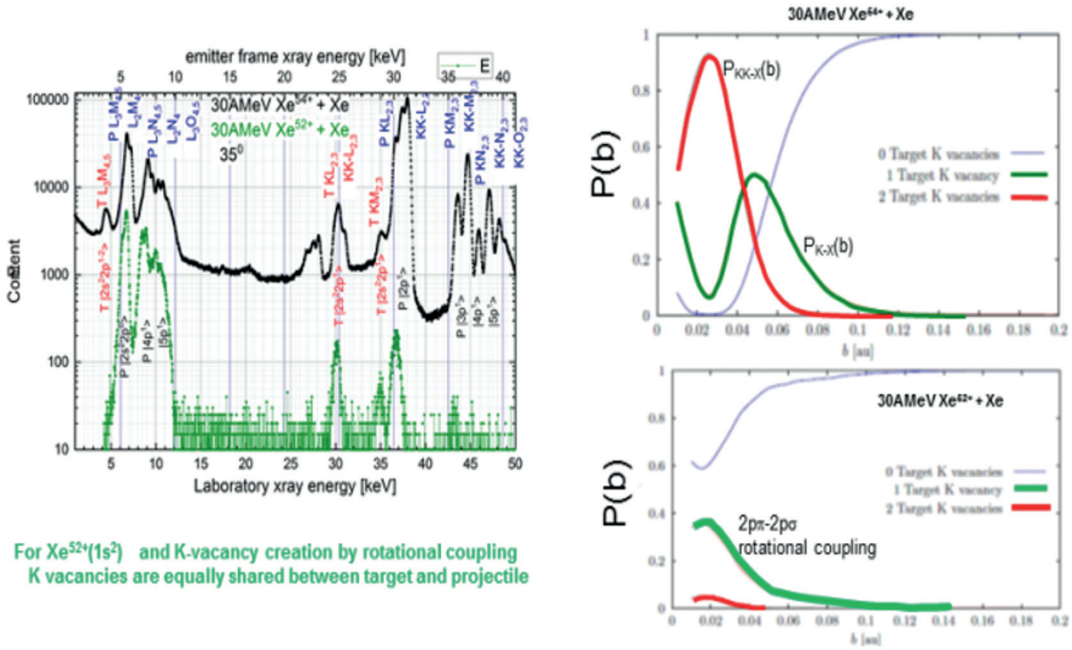


Figure 10. Preliminary x-ray spectra measured under 35° for collisions of $Xe^{52+}(1s^2)$ and bare Xe^{54+}+ Xe at 30 MeV/u. Due to the Doppler shift, the projectile and target radiation are energetically well separated. The strong influence of incoming K vacancies is visible for the x-ray spectrum produced by bare Xe^{54+}. Both, target and projectile K-shell x rays show the characteristic structure of satellite and hyper-satellite radiation originating from target single- and double K-shell vacancy production. On the right hand side the theoretical impact parameter dependence for target K-vacancy production probability is compared for projectiles with and without incoming K vacancies.

Electron capture of Xe^{54+} in collisions with low-Z target molecules at low beam velocities

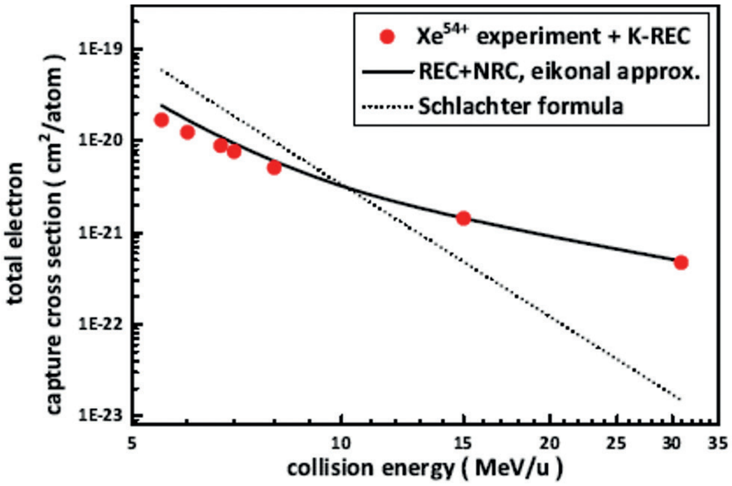


Figure 11. Total electron capture cross section data for collisions of bare Xenon ions with H_2 target molecules in comparison to theory and a semi-empirical formula.

The electron capture process was studied for Xe^{54+} ions colliding with H_2 molecules at the internal gas target of the ESR storage ring at GSI, Darmstadt. Cross section values for electron capture into excited projectile states were deduced from the observed emission cross sections of the Lyman radiation, being emitted by the H-like ions subsequent to the capture of a target electron. The ion beam energy range was varied between 5.5 MeV/u and 30.9 MeV/u by applying the deceleration mode of the ESR. Thus, electron capture data was recorded at the intermediate and in particular the low collision energy regime, well below the beam energy necessary to produce bare xenon ions. The obtained data is found to be in reasonable qualitative agreement with theoretical approaches (although the deviation between experiment and theory increases with decreasing beam energy), while a commonly applied empirical formula significantly overestimates the experimental findings. Note, these findings are of utmost importance for future experiments at CRYRING@

ESR where electron capture at these low-beam energies constitutes the most critical limitation of beam lifetimes and put serious constraints on the ultra-high vacuum conditions of the ring. Therefore, more detailed experimental data are urgently needed.

F. M. Kröger et al., Phys. Rev. A 102, 042825 (2020), DOI:10.1103/PhysRevA.102.042825

Radiative electron capture to the continuum in U^{89+} - N_2 collisions: Experiment and theory

For U^{89+} projectiles colliding at a beam energy of 76 MeV/u with a N_2 target, we performed a coincidence measurement between the cusp electrons emitted under an angle of 0 deg with respect to the projectile beam and the photons emitted under a polar angle of 90 deg. This radiative-electron-capture-to-continuum cusp directly probes the theory of electron-nucleus bremsstrahlung up to the high-energy endpoint in inverse kinematics. In the present study, significant improvement with respect to the experimental accuracy has been achieved, resulting in a finer agreement between experimental and theoretical results.

P.-M. Hillenbrand et al., Phys. Rev. A 101, 022708 (2020), DOI:10.1103/PhysRevA.101.022708

Experiments at CERN and DESY

New measurement exacerbates old problem (PETRAIII at DESY)

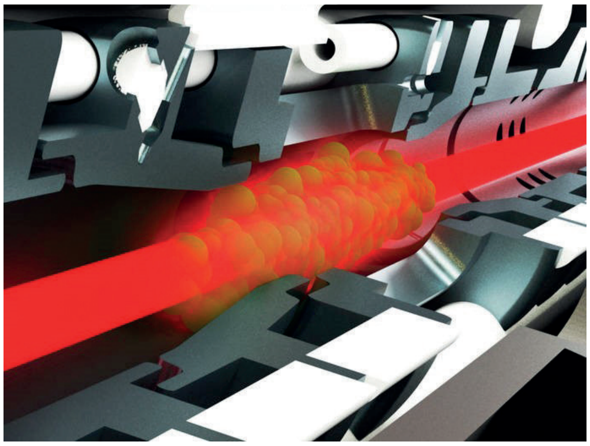


Figure 12. A cloud of trapped iron ions interacting with intense X-rays from a synchrotron light source (Illustration: S. Bernitt, Helmholtz Institute Jena).

Two prominent x-ray emission lines of highly charged iron have puzzled astrophysicists for decades: their measured and calculated brightness ratios always disagree. This hinders good determinations of plasma temperatures and densities. New, careful high-precision measurements together with top-level calculations now exclude all hitherto proposed explanations for this discrepancy, and thus deepen the problem. Therefore, astrophysical parameters derived on the basis of x-ray line intensities are, to some degree, uncertain. While this is unsatisfactory, “the new accurate experimental result may be immediately used to empirically correct the astrophysical models”, recommends Maurice Leutenegger, a NASA researcher involved in the experiment - “Upcoming space missions with advanced x-ray instrumentation, such as ESA’s Athena x-ray Observatory, will soon start sending an incredible stream of high-resolution data to ground, and we have to be prepared to understand it and squeeze the maximum value from those billion-dollar investments.” The experiment was performed at PETRA III at DESY by using an Electron Beam Ion Trap.

Steffen Kühn et al., Phys. Rev. Lett. 124, 225001 (2020), DOI:10.1103/PhysRevLett. 124.225001

Mass of the deuteron corrected (AD at CERN)

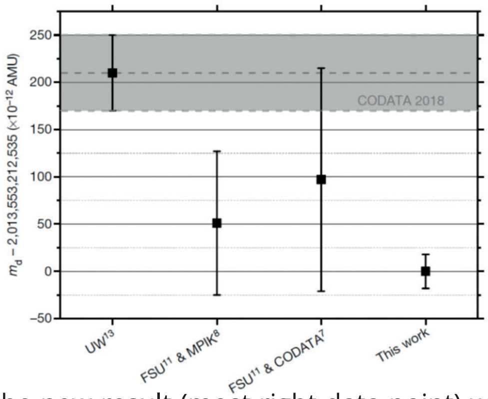


Figure 13. Comparison of the new result (most right data point) with literature data and the CODATA value (grey shaded area).

High-precision measurements of the mass of the deuteron, the nucleus of heavy hydrogen, provide new insights into the reliability of fundamental quantities in atomic and nuclear physics. This is reported in the journal “Nature” by a collaboration led by the Max Planck Institute for Nuclear Physics Heidelberg and partners from the Johannes Gutenberg University Mainz, the Atomic Physics Department of GSI Helmholtz Centre for Heavy Ion Research Darmstadt and the Helmholtz Institute Mainz. Thus, data directly related to the atomic mass standard, are now available for hydrogen H, deuterium D and the molecule HD, which the scientists have also reweighed. For the specific case of D, the total mass has been determined to m_d = 2.013 553 212 535 (11)stat(13) sys(17)tot u, and hence with an accuracy of $\Delta m/m = 8\text{x}10^{-12}$ (see Figure 13) provides a comparison with already available data published in literature, proving that the new experimental result provides a substantial correction.

S. Rau et al., Nature 585, 43 (2020), DOI:10.1038/s41586-020-2628-7

Selected publications of 2020

- [1] Leutenegger, M. A. ; Kühn, S. ; Micke, P. ; et al: High-Precision Determination of Oxygen K_α Transition Energy Excludes Incongruent Motion of Interstellar Oxygen. Physical review letters 125(24), 243001 (2020) DOI:10.1103/PhysRevLett.125.243001
- [2] Popov, R. V. ; Shabaev, V. M. ; Telnov, D. A. ; et al: How to access QED at a supercritical Coulomb field. Physical review / D 102(7), 076005 (2020) DOI:10.1103/PhysRevD.102.076005

All publications of 2020 are listed in the GSI Repository.

2.2 Department Materials Research

Head: Prof. Dr. Christina Trautmann, Technische Universität Darmstadt & GSI
Author: Christina Trautmann, Lars Breuer (Univ. Duisburg/Essen), Maria Eugenia Toimil-Molares, Verena Velthaus

The operation of the user platform for materials science and various interdisciplinary fields was continued at (i) the UNILAC M-branch for on-line and in situ monitoring of beam induced effects, (ii) the UNILAC X0-beamline for high through-put irradiations and single-ion targeting at the microprobe, and (iii) the SIS 18 Cave A for experiments requiring ion ranges of mm and more. Due to the pandemic, the beamtime block in 2020 has been challenging, but in spite of the many restrictions about two thirds of the scheduled irradiation experiments were successfully completed. Research topics comprised track formation and damage processes [1, 2], radiation hardness tests of FAIR relevant materials [3], electronic sputtering and beam-induced desorption (cf highlights), radiolysis of complex organic molecules in space, and ionoacoustics. Research activities on nanostructures fabricated by means of ion-track technology focussed on nanochannel-based sensors [4] as well as on semimetal and semiconductor nanowire arrays or networks for applications e.g. in thermoelectrics (cf highlights) and photoelectrochemistry [5].

Technical developments at the M-branch comprise in-situ Raman spectroscopy and a new fs-laser system for neutral mass spectrometry (cf. highlights). At the CRYRING, the irradiation and analysis chamber dedicated to material science was installed at the extraction beam line and is now connected to the storage ring.

Highlights in 2020

Secondary Ion and Neutral Mass Spectrometry (SIMS/SNMS) at M-branch

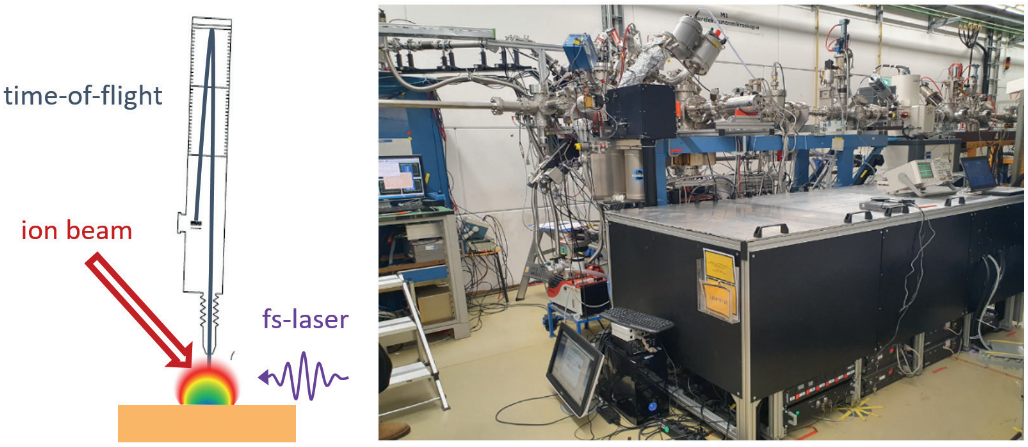


Figure 14. (Left) Scheme of secondary ion and neutral mass spectrometry setup at the M-Branch for sputter experiments under swift heavy ion bombardment. The laser beam is injected parallel to the sample surface and post-ionizes neutral particles which are then analysed in the time-of-flight spectrometer. (Right) The new fs-laser coupled to the irradiation chamber at the M1 beamline consists of a 800 nm Ti:Sapphire oscillator and a chirped pulse amplification system delivering 10 mJ pulses with a repetition rate of 1 kHz and 40 fs pulse duration at 800 nm and NIR (1150 -2600 nm) in combination with an optical parametric amplifier delivering pulses up to 2.5 mJ.

Sputtering processes in the electronic energy loss regime are investigated with the in-situ SIMS/SNMS setup at the M1-beamline (Verbundforschungsprojekt 05K19PG1, Prof. A. Wucher et al.). Secondary ions ejected from the surface under swift heavy ion bombardment are directly analysed by time-of-flight mass spectrometry. Since the majority of the sputtered ejecta are neutral, the technique of post-ionization via laser-induced photo ionization has been established. In 2020, the existing post-ionization laser (pulsed F2 laser operated at a VUV wavelength of 157 nm) was complemented by the installation of a new fs-IR laser system (see Figure 14) which provides fs strong field ionization and thus allows species independent analysis. With the upgraded system important sputtering parameters will become accessible such as the velocity and energy distribution of the emitted neutrals as well as their size and chemical composition.

Desorption measurements of accelerator-related materials exposed to different stimuli

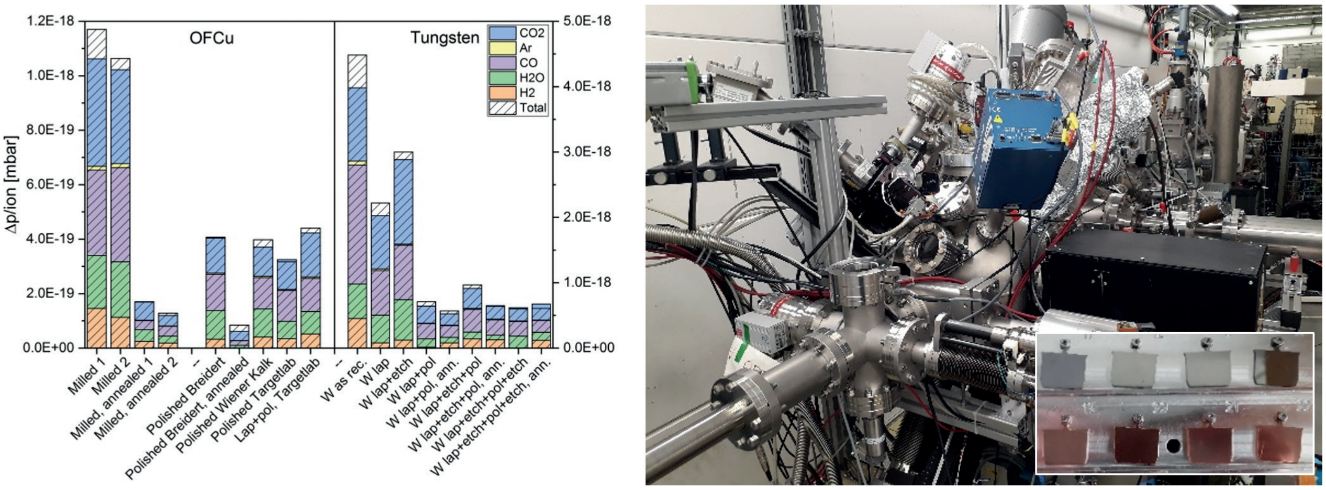


Figure 15. (Left) Experimental results from ion-beam induced desorption measurements of oxygen-free Cu and W samples bombarded with 4.8 MeV/u Ca^{19+} ions. The samples were pre-treated by a variety of annealing and polishing procedures. The gas released is mainly composed of H_2, H_2O, CO and CO_2. (Right) Experimental UHV station at the M1-beamline for desorption experiments including an extractor gauge and a quadrupole mass spectrometer to monitor the pressure increase during irradiation. The inset shows the standardized samples inserted via a load lock system.

High-energy particle accelerators require low desorbing components to minimize beam-induced pressure rises leading to serious losses in beam intensity. To test different treatment procedures for achieving low-desorbing surfaces, an experimental campaign was conducted at the M-branch. The experiments in 2020 focussed on mechanical surface treatments such as milling, lapping and polishing and thermal annealing for oxygen-free copper (OFCu) and tungsten samples. We could show that ex-situ thermal annealing at 400 °C in ultra-high vacuum (UHV) for about 4 hours (details depend on the pressure evolution during annealing) is a simple but very effective tool to reduce thermal and ion-beam induced desorption (see Figure 15). Moreover, a clean and smooth surface is an important factor which can be achieved by milling and polishing. The measurements at the M-branch were complemented by off-line thermal- and electron-stimulated desorption tests in a dedicated UHV chamber. Electron-stimulated desorption with keV electrons seems to be primarily a surface related process. Outgassing yields of the tested materials differ only slightly and coating with gold shows no dependence on layer thickness, diffusion barrier or coating technique. In contrast, thermal desorption is strongly related to bulk processes. Even after several weeks of storage in atmosphere, thermal stimulated gas desorption of samples UHV-annealed at 400 °C is significantly reduced. Pre-treating critical accelerator component at such conditions is highly recommended for lowest possible desorption.

Ion-track nanotechnology

Thermoelectrical properties of highly interconnected nanowire networks

Nanowire networks consist of macroscopic areas of highly interconnected nanowires. Due to their adjustable size (up to several cm^2), they can be easily handled and integrated in larger set-ups and devices. The numerous junctions between adjacent nanowires in an interconnected network renders mechanical stability and high electrical reliability. Such nanowire networks are fascinating systems, because they can be handled like macroscopic objects while exhibiting properties of nanoscale materials. Nanowire networks are of special interest for various emerging applications such as microelectronic devices, thermoelectric sensing, transparent conductors, or selective catalysis for green fuels [4,5]. Free-standing 3D semimetal bismuth nanowire networks with well-controlled and systematically adjusted wire diameter and interconnectivity were fabricated by pulsed electrodeposition of bismuth into the pores of ion track-etched membranes (see Figure 16, left). Cross-plane Seebeck coefficient and electrical resistance values were studied as a function of wire diameter and temperature (see Figure 16, right). With decreasing temperature, all samples displayed a sign change from a negative to a positive Seebeck coefficient. The smaller the wire diameter, the higher the transition temperature. This behaviour was attributed to the mean free path limitation of the charge carriers for small wire diameters and is in good agreement with theoretical predictions. For wire diameters below 140 nm, the size effect observed for the Seebeck coefficient is also attributed to limitations of the mean free path as well as contributions of surface states to the transport properties. Moreover, size effects contribute to the diameter-dependent non-monotonic behaviour of the electrical resistance of bismuth nanowire networks as a function of temperature. The unique characteristics of the Bi nanowire networks offer exciting perspectives for their implementation, e.g., in infrared detection systems based on thermoelectric effects, sensorics, and THz applications.

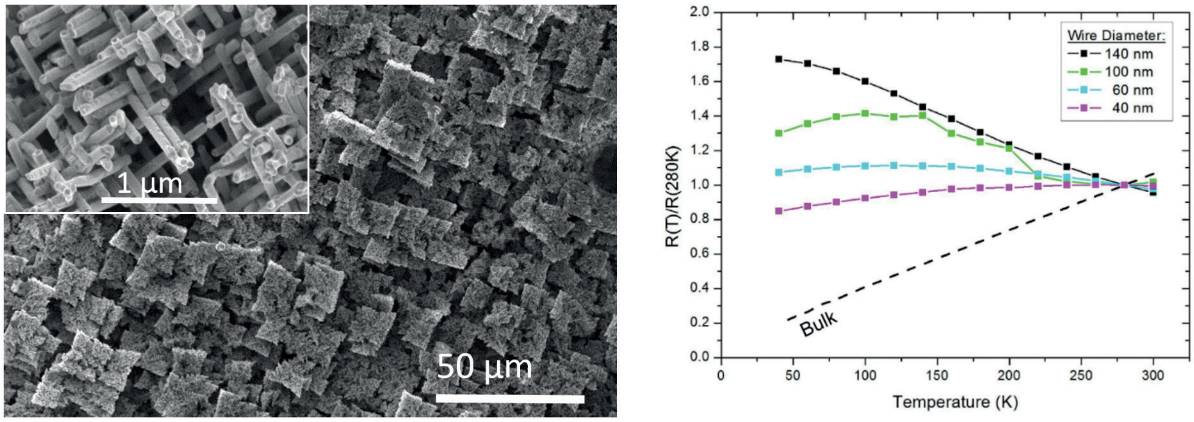


Figure 16. (Left) Scanning electron micrographs of Bi nanowire networks fabricated by electrodeposition of Bi into track-etched membranes. (Right) Temperature dependence of the electrical resistance of the 3D Bi-networks for different wire diameters (M.F. Wagner et al., Advanced Electronic Materials (2021) 2001069 DOI:10.1002/aelm.202001069).

Outlook for 2021

At all MAT beamlines the FAIR Phase-0 will be continued with beamtime in spring 2021 and 2022. The MAT target station at the extraction beam line of the CRYRING is ready for commissioning. First experiments with highly charged or completely stripped ions injected from SIS18 and ESR are expected for the beamtime block in 2021 and 2022. Moreover, the installation of an in-situ confocal UHV-Raman spectrometer is planned.

Selected publications of 2020

- [1] Lang, M. ; Djurabekova, F. ; Medvedev, N. ; et al: Fundamental Phenomena and Applications of Swift Heavy Ion Irradiations [Part 1.15]. In: Comprehensive Nuclear Materials / Lang, Maik; Elsevier, 2020; ISBN: 9780081028667, Oxford: Elsevier, : 2nd ed, 485-516 (2020), DOI:10.1016/B978-0-12-803581-8.11644-3
- [2] Lang, M. ; O'Quinn, E. ; Neuefeind, J. ; et al: Characterization of Radiation Effects and Ion Tracks with Spallation Neutron Probes. Nuclear physics news 30(1), 16 - 19 (2020), DOI:10.1080/10619127.2019.1676120
- [3] Prosvetov, A. ; Hamaoui, G. ; Horny, N. ; et al: Degradation of thermal transport properties in fine-grained isotropic graphite exposed to swift heavy ion beams. Acta materialia 184, 187 - 198 (2020), DOI:10.1016/j.actamat.2019.11.037
- [4] Laucirica, G. ; Albesa, A. G. ; Toimil Molares, M. E. ; et al: Shape matters: Enhanced osmotic energy harvesting in bullet-shaped nanochannels. Nano energy 71, 104612 (2020), DOI:10.1016/j.nanoen.2020.104612
- [5] Yang, F. ; Schröck, C. ; Kugelstadt, J. ; et al: Cu_2O/TiO_2 Nanowire Assemblies as Photocathodes for Solar Hydrogen Evolution: Influence of Diameter, Length and NumberDensity of Wires. Zeitschrift für physikalische Chemie 234(6), 1205-1221 (2020), DOI: 10.1515/zpch-2019-1529

2.3 Department Plasma Physics

Head: Dr. Vincent Bagnoud, GSI
Authors: V. Bagnoud, P. Hesselbach, O. Rosmej, S. Götte, P. Neumayer, M. Zimmer (TU Darmstadt), S. Scheuren (TU Darmstadt), M. Roth (TU Darmstadt), J.-R. Marquès (LULI, France), M. Tarisien (CENBG, France)

The Plasma Physics department at GSI operates several experimental caves: the Z6 cave in the experimental hall of the UNILAC, the high-energy cave HHT at the output of the SIS18 synchrotron, and the petawatt target area at PHELIX. These caves enable pursuing a worldwide-unique experimental program involving laser and ion beam experiments. In addition, the department is involved in the preparation of the high-energy-density experiments at FAIR, both technically and scientifically [1].

During the early part of 2020, UNILAC ion-beam operation at the Z6 experimental area took place (Experiment U317). Despite the pandemic, nine experiments were conducted by external groups at PHELIX (one with nhelix), with only one experiment shifted to summer 2021. To make this possible, an increased dedication of the department staff was necessary to allow users to control the experiments remotely. In addition, at the peak of the pandemic-related restrictions, extended shifts and additional time was devoted to operation in order to cope with the severe work place occupancy restrictions. Overall, the year turned out nearly normal in terms of operation with 57% of the year dedicated to experiments (long -term average is 63%) and a 9-week maintenance block dedicated to the upgrade of the short-pulse front end in the framework of the ATHENA project in the fall.

For PHELIX, the main development has dealt with its frontend, where a new parametric amplifier has been brought into operation. This amplifier has been financed via the ATHENA project and is supported by the Loewe center for Nuclear Photonics in Darmstadt. The project follows a phased approach, and a first low-power version of the amplifier was deployed at PHELIX, awaiting validation in real operation conditions in the next months. After validation and a gradual increase of the performance in 2021, the system will be replicated for the Penelope laser at the Helmholtz Center Dresden-Rossendorf in 2021.

The most intense development for the department has been at the high-energy cave HHT at the output of the SIS18 accelerator. There, the proton microscope PRIOR developed for FAIR, driven by GeV protons from SIS18, has been installed during the summer and fall and fully aligned during the dry runs at the end of the year. In addition, the construction work to connect PHELIX to the HHT cave has continued. The largest part of the procurement was placed in 2020 and the installation of the components has already begun. Most noticeably, the laser laboratory on top of the cave has been built and commissioned and all other preparatory work successfully finished in coordination with GSI's infrastructure departments.

The beam time in the Plasma Physics caves, as for all other experimental areas at GSI, is decided by GSI's directorate based on the recommendations of advisory committees. In 2020, the PPAC met in October to make recommendations on experiment proposals using PHELIX. This was the opportunity to reassess the attractiveness of the facility and the strong demand to use it as secondary source [2, 3], like for laser-driven fission experiments [4]. In addition, the PPAC and GPAC met in the spring to distribute beam time for plasma physics experiments using both UNILAC and the SIS18 accelerator facilities. The new beam time block starts in winter/spring 20/21.

Scientific highlights in 2020

Development of improved laser-driven x-ray sources for FAIR

A major challenge for high-energy-density experiments at FAIR will be to diagnose the heated samples under investigation. The brilliance of laser-driven x-ray sources, when coupled to advanced x-ray-based measurement methods, enables the implementation of versatile diagnostics. However, a major challenge concerning these x-ray sources is the production of large numbers of high-energy photons above 10 keV when laser intensity is limited to 10^{15} W/cm^2, as it is the case for Day-1 experiments at FAIR and PHELIX-driven experiments at HHT in the FAIR Phase-0. The higher the photon energy is, the higher the densities and thicknesses of samples for which the diagnostics are applicable. Since a unique characteristic of the GSI facility is the possibility to heat mesoscopic samples, high photon energies are required to make full use of the ion heating capabilities when combined with x-ray diagnostics. This issue was addressed in collaboration with a research group from LULI, France, during the experimental campaign P203 at the Z6 experimental station using PHELIX nanosecond pulses with energies up to 200 J (in 1.5 ns) at a wavelength of 527 nm.

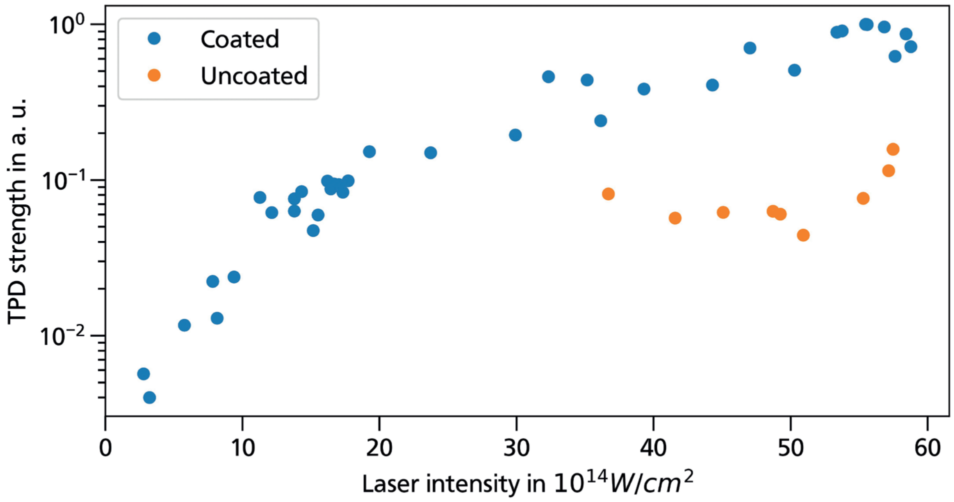


Figure 17. Two-plasmon-decay signal in laser-plasma interaction experiment driven by PHELIX for two types of targets.

To increase the number of high-energy photons, one possibility exploits a plasma parametric instability, the Two-Plasmon-Decay (TPD), which is known for boosting the hot-electron production. These electrons in turn generate x-ray emission with high photon energies via bremsstrahlung or line emission in materials with high nuclear numbers. Usually, TPD is popular in the field of Inertial Confinement Fusion (ICF) research, where it displays a disturbing effect causing preheat of the fuel capsule [D. H. Froula et al., Phys. Rev. Lett. 108 (16), 165003 (2019)]. While TPD is to be mitigated as much as possible for ICF, the aim of the experiment was, on the opposite, to experimentally optimize the conditions for TPD. For that purpose, the research team used metallic targets with a plastic coating, which result in faster pre-plasma expansion compared to bare metallic targets. In addition, the decreased density gradient with plastic targets facilitates TPD, which only occurs in a small density range of the underdense plasma. The targets were provided by the LULI group and their design was based on a previous experiment at the National Ignition Facility, USA [S. Le Pape et al., High Energy Density Physics 31, 13-18 (2019)].

While the experimental data is still being analyzed, the first observations look promising in terms of increasing photon numbers at high energies by optimizing TPD (see Figure 17). The coated target design resulted in a clear increased TPD signal strength compared to bare targets. Based on this data, a clear optimization path can be identified for the specific PHELIX parameters, if the laser spot size is optimized, for instance. Such an optimization can be achieved by a suitable phase plate and be tested in a future experimental campaign. The enhancement in photon numbers at high energies is expected to be significant compared to conventional laser-driven x-ray sources.

Demonstration of material analysis via laser-driven-neutron spectroscopy

Neutrons are a valuable tool for non-destructive material characterization. Their unique ability to distinguish between different isotopes of the same element together with their high penetration depth through high-Z materials makes them a complementary diagnostic to x-rays. While there is a high demand on neutron sources from science and industry, only a few large-scale accelerator-driven sources have the capability of producing neutron pulses short enough to apply time-of-flight based material characterization techniques like neutron resonance spectroscopy or neutron resonance imaging. Neutron sources driven by high-intensity lasers are an attractive alternative to produce suitable neutron pulses with a more compact design [M. Roth et al. Phys. Rev. Lett. 110, (2013)]. Previous experiments with laser-neutron sources focused on neutron characterization and the utilization of fast neutron beams for radiography [R. O. Nelson et al., J. Imaging 4, 1–26 (2018)].

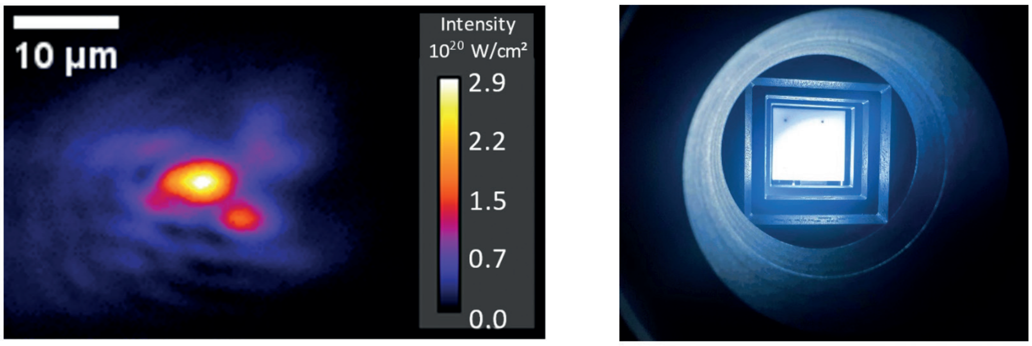


Figure 18. Left: Intensity profile of the laser focus on target. Right: Neutron Moderator (white) together with the collimation system for epi-thermal neutrons.

In the experiment P197 at PHELIX (see Figure 18), a research group from the Technical University of Darmstadt has successfully slowed laser driven neutrons down into the thermal and epithermal regime and used a collimation system to enable the usage a time-of-flight based material characterization methods [3]. The neutrons were produced via accelerating deuterium ions from sub-micrometer-thick targets via the target normal sheath acceleration mechanism and directing them on a lithium-fluoride converter. A polyethylene moderator designed to maximize the epithermal neutron flux was located downstream to slow down the neutrons subsequently. The collimation system consisted of five layers of borated polyethylene with a converging recess to minimize background contributions.

With this neutron beam, it was possible to demonstrate that the setup can be used to non-destructively identify the thickness of samples, their isotopic composition as well as the spatial distribution of isotopes inside a sample.

Laser acceleration of protons in an over-critical plasma slab produced by the collision of blast-waves in a gas jet

In the experimental campaign P189, two research groups from LULI and CENBG from France studied a new laser-ion acceleration scheme from an innovative gaseous target. High-density gas jets are self-regenerative debrisless targets that are particularly suitable for high-repetition-rate laser operation. They are produced by sub-millimeter supersonic nozzles capable to generate the required near critical plasma densities for high-energy ion acceleration in the laser direction. However, due to limitations imposed by available mechanical machining technologies, the gas density profiles delivered are Gaussian-like and lasers interact with low-density tails before reaching their high density central part of interest. These interactions induce moderate ion acceleration in the laser transverse direction as observed in [P. Puyuelo-Valdes et al., Phys. Plasmas 26, 123109 (2019)]. In order to minimize these parasitic interactions, additional tailoring of the gas jet density profile has been suggested [J.-R. Marquès et al., Phys. Plasmas 28, 023103 (2021)].

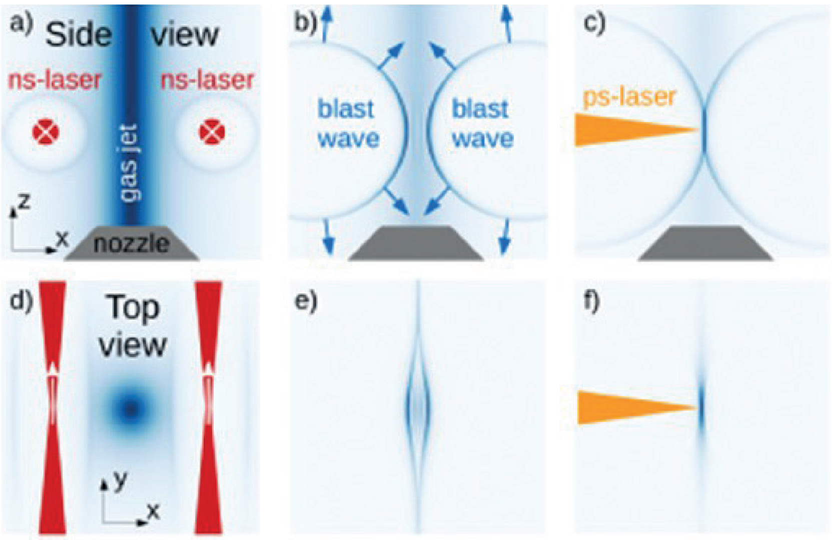


Figure 19. Principle of the plasma tailoring. a)-c): side view (from y-axis) of the gas jet (blue column), that exits the nozzle along the z axis; d)-f) top view (from z-axis).

The proof-of-principle experiment took place at PHELIX, GSI in order to achieve plasma tailoring of a high-density gas jet by the use of colliding blast waves, as depicted in Figure 19. The two synchronized nanosecond laser beams (red) propagate parallel to the y-axis, on both sides of the gas jet. The sudden laser heating of the plasma induces steep density fronts (a, d) that propagate out of the laser axis as blast waves (b, e). The collision of two blast waves at the center of the gas jet (c, d) produces a sharp-gradient, thin, high-density plasma.

Detailed numerical simulations of the modified achievable gas jet density profiles have been made before the experiment. The research group demonstrated that proton acceleration from a high-density gas jet is more efficient, when the latter is optically tailored on both the entrance and exit sides of the driving picosecond laser pulse. In addition, a transition from a continuous (exponential) to a peaked energy spectrum is observed, when the gas jet is optically shaped.

Ion beam imaging with X-ray Conversion to Optical and Transport (XCOT)

The x-ray emission generated by swift heavy ions crossing a target can be exploited to retrieve the ion beam distribution on target. Based on that principle, the X-ray Conversion to Optical Radiation and Transport (XCOT)-system is being developed at the Goethe University, Frankfurt for applications at the APPA cave at the FAIR accelerator, where uranium beams will be delivered by SIS100 for high-energy-density experiments. The system will provide a key information on the spatial ion-beam distribution on target, at ultra-high ion-beam intensities in every shot.

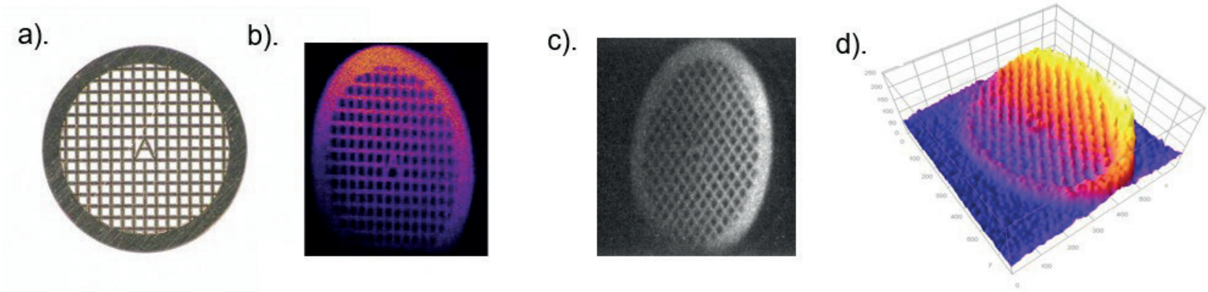


Figure 20. (a) Cu150-mesh; (b) monochromatic x-ray image of the mesh built by the Si-crystal at x-ray CCD camera; (c) visible image detected by the sCMOS-camera; (d) reconstructed Au-beam intensity distribution on the mesh.

Two different setups of the XCOT-system were tested in experiments at the UNILAC (experiment U317) using 8.6-11.4 MeV/u gold-beam: Polychromatic imaging using multi-pinhole cameras (see GSI Sci. Rep. 2019) and a mono-chromatic imaging technique that uses a toroidally bent silicium

(444) crystal produced in FSU, Jena. In the monochromatic imaging scheme, the 2D x-ray image of the copper mesh irradiated with gold ions was imaged by the copper-K-Alpha (8 keV) crystal imager on a CsI(Tl) scintillator with a magnification of factor 7. The mesh image, converted into visible light, was registered by an intensified sCMOS camera. Both the scintillator and the camera were placed out of the vacuum chamber in air.

Figure 20(a) shows a 3-mm-diameter and 10-µm-thick copper 150 mesh. The silicium-crystal images a monochromatic x-ray image of the copper mesh irradiated with gold ions onto an x-ray CCD camera (Figure 20(b)) and/or onto a sCMOS camera, after its conversion by the CsI(Tl) scintillator into visible light (Figure 20(c)). Figure 20(d) presents the reconstructed gold-ion-beam intensity distribution on the mesh that reveals an inhomogeneity in the irradiation.

Outlook for 2021

2021 will continue to see a strong focus on the preparation of the infrastructure and experiments at HHT as the workhorse for many upcoming FAIR-related activities supported by the high-energy density community. Beamtime for PRIOR has been secured for its commissioning, and early experiments are planned at the beginning of the next ion beam block. In addition, we expect the commissioning of the laser capabilities at the HHT cave to support the diagnostic development for FAIR and the intermediate research program FAIR Phase-0. ATHENA will continue in 2021 with the goal to make a full-performance demonstration on the new frontend for PHELIX and the delivery of a copy to the Helmholtz Center Dresden Rossendorf.

Selected publications of 2020

- [1] Schoenberg, K. ; Bagnoud, V. ; Blazevic, A. ; et al.: High-energy-density-science capabilities at the Facility for Antiproton and Ion Research. Physics of plasmas 27(4), 043103 (2020), DOI:10.1063/1.5134846
- [2] Rosmej, O. ; Gyrdymov, M. ; Günther, M. ; et al: High-current laser-driven beams of relativistic electrons for high energy density research. Plasma physics and controlled fusion 62(11), 115024 (2020), DOI10.1088/1361-6587/abb24e
- [3] Hornung, J. ; Zobus, Y. ; Boller, P. ; et al: Enhancement of the laser-driven proton source at PHELIX. High power laser science and engineering 8, e24 (2020), DOI:10.1017/hpl.2020.23
- [4] Boller, P. ; Zylstra, A. ; Neumayer, P. ; et al: First on-line detection of radioactive fission isotopes produced by laser-accelerated protons. Scientific reports 10(1), 17183 (2020), DOI:10.1038/s41598-020-74045-5
- [5] Zimmer, M. ; Scheuren, S. ; Kleinschmidt, A. ; et al: Development of a Setup for Material Identification Based on Laser-Driven Neutron Resonance Spectroscopy. 8th International Meeting of Union for Compact Accelerator-Driven Neutron Sources, UCANS-8, Paris, France, 8 Jul 2019 - 11 Jul 2019 The European physical journal / Web of Conferences 231, 01006 (2020), DOI:10.1051/epjconf/202023101006

2.4 Biophysics department

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

The Biophysics Department studies the biological and medical applications of high-energy heavy ions, with two main applications: cancer therapy and space radiation protection. It is a highly interdisciplinary department, with over 90 members with background in physics, biology, chemistry, and engineering. The Biophysics Department is part of the APPA pillar at FAIR.

Figure 21. Meeting of the executive committee of the Biophysics Collaboration held in Rome (Italy) on February 20-21, 2020. In addition to the Biophysics Department (GSI/FAIR), the committee includes representative of other accelerators in operation (HIMAC, CNAO, GANIL, LNS, LNL, iThemba, KVI), or under construction (NICA, RAON, ELI). Image by Prof. Durante, reproduced with permission of all participants.

Biophysics Collaboration at FAIR

The Biophysics Collaboration (Figure 21) is a large network of accelerator facilities in operation or under construction with scientific programs in biomedical applications. The collaboration has produced in 2020 a special issue of the journal Frontiers in Physics titled Applied Nuclear Physics at Accelerators. 56 scientific papers were published in this issue, one of the highest number for any issue of the same journal.

Funding

The Biophysics Department has been successful in 2020 in collecting third-party funds reaching a total of 7.9 M€ funding from German, EU, and US funding agencies. Among the most important awards, an ERC Advanced Grant (2.5 M€) to Prof. Durante for a project in collaboration with NuSTAR and LMU to exploit radioactive ion beams in radiotherapy (BARB). The Department is also involved in three EU Research Infrastructure projects, one Marie Curie and one EURATOM. Together with the MD Anderson Cancer Center (Houston, TX) we were also funded by NIH in USA to study the effect of protons and heavy-ions in organoids mimicking human brains containing a glioblastoma tumour.

Awards

Several members of the Biophysics Department received awards in 2020. Particularly relevant are the Hermann-Holthusen-Preise of the German Society of Radio-oncology (DEGRO) to Dr. Thomas Friedrich and the Gioacchino Failla award of the US Radiation Research Society (RRS) to Prof. Marco Durante, the most prestigious award of the RRS.

Highlights in 2020

In the framework of FAIR Phase-0, our Department has performed several experiments in the first half of the year using high-energy H, C and Fe-ions. The COVID-19 lockdown forced the cancellation of some experiments performed by external groups within the ESA-IBER program, but the majority of experiments have been performed. A few highlights are described 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. This high intensity cannot be achieved with X-rays, but has been tested with electrons and protons, accelerated in cyclotrons. For the first time we have proved, using the SIS18 synchrotron, that these ultra-high dose-rates can also be achieved with C-ions. With the setup in Figure 23 we were indeed able to deliver 14 Gy of 240 MeV/n ^{12}C-ions in 200 ms. The biological experiment has been approved by the Bio-Programme Advisory Committee and will be performed in the year 2021.

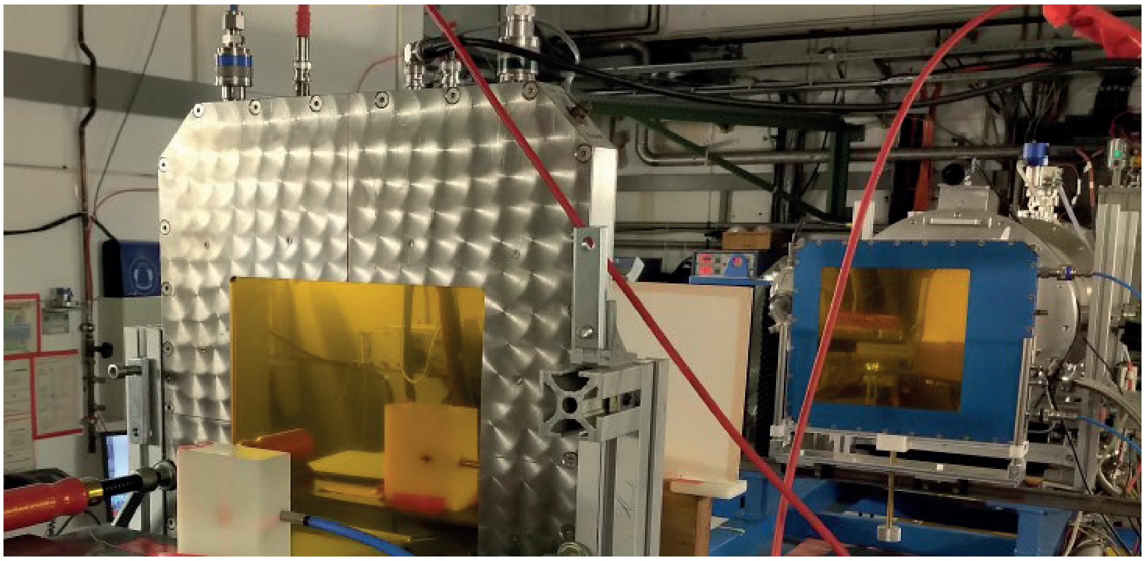


Figure 22. Experimental setup in Cave A for FLASH radiotherapy tests with heavy ions. The intensity monitor is a He-filled parallel-plate ionization chamber and the dose is measured with a pinpoint chamber in a polyethylene block. Photo by Dr. Uli Weber, reproduced under CC-BY 3.0 license.

ROSSINI

The ROSSINI experiment has been concluded in 2020 at GSI with the final tests of lithium hydrides using the setup in Figure 23. ROSSINI is a project funded by ESA and performed in collaboration with THALES Alenia Space and the Chemistry Department of the Turin University (Italy). We have demonstrated that LiH has exceptional shielding properties against 1 GeV/n ^{56}Fe-ions, used as a proxy of heavy-ions in the galactic cosmic rays. Lithium hydrides are therefore an ideal material to protect astronauts in a mission to Mars. However, they present servere hazard problems for spaceflight, which can be mitigated by embedding the lithium in plastics.

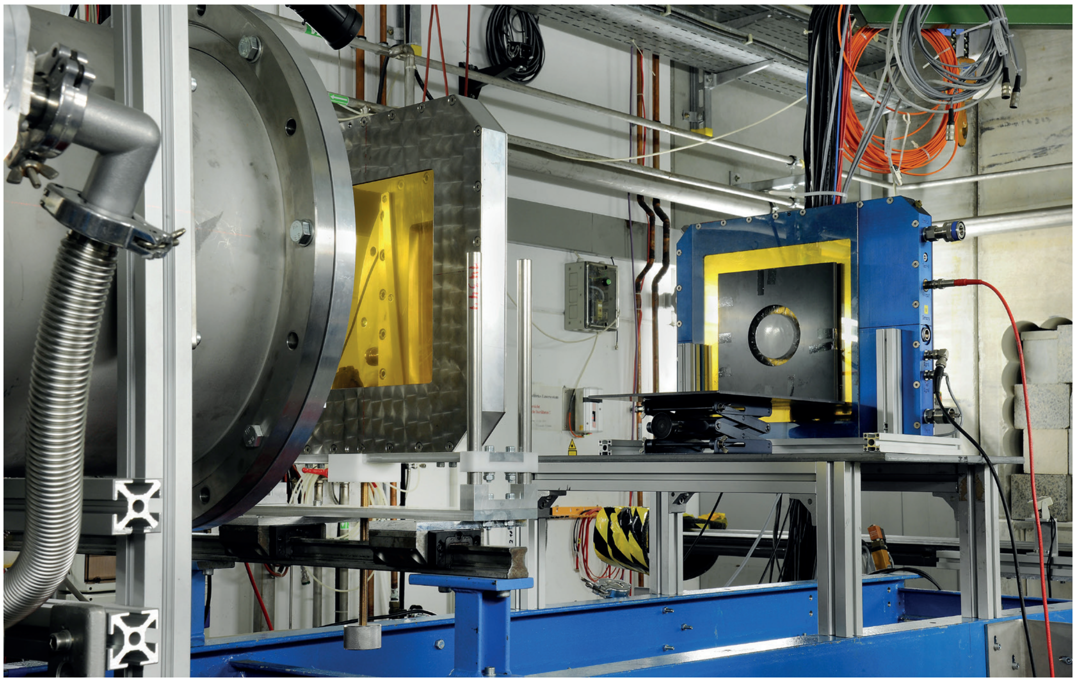


Figure 23. Experimental setup in Cave A for measurements of shielding material properties against simulated cosmic rays. A LiH pellet is mounted in the gray frame on the right of the photo. Image by Dr. Christoph Schuy, reproduced under CC-BY 3.0 license.

Outlook for 2021

Twenty-seven proposals have been submitted to the Bio-PAC in June 2020. Many exciting experiments will be performed in the coming FAIR Phase-0 including the ERC-BARB and FLASH experiments, a test of the TRON/BioNTech vaccine against cancer in combination with C-ions, irradiation of the SARS-CoV-2 virus with heavy ions for vaccine development, and use of minibeams with heavy ions to reduce the toxicity. The ESA-IBER will be also continued implementing a dozen of experiments from all over Europe with high-energy Fe-ions.

Selected publications of 2020

- Durante, M. ; Formenti, S.: Harnessing radiation to improve immunotherapy: better with particles? The British journal of radiology 93(1107), 20190224 (2020) DOI:10.1259/bjr.20190224
- Reidel, C.-A. ; Schuy, C. ; Horst, F. ; et al.: Fluence perturbation from fiducial markers due to edge-scattering measured with pixel sensors for 12C ion beams. Physics in medicine and biology 65(8), 085005 (2020) DOI:10.1088/1361-6560/ab762f 762f Open Access
- Tinganelli, W. ; Durante, M.: Carbon Ion Radiobiology. Cancers 12(10), 3022 (2020) DOI:10.3390/cancers12103022 Open Access
- Jakob, B. ; Dubiak-Szepietowska, M. ; Janiel, E. ; et al.: Differential Repair Protein Recruitment at Sites of Clustered and Isolated DNA Double-Strand Breaks Produced by High-Energy Heavy Ions. Scientific reports 10(1), 1443 (2020) DOI:10.1038/s41598-020-58084-6 Open Access
- Lis, M. ; Donetti, M. ; Newhauser, W. ; et al.: A modular dose delivery system for treating moving targets with scanned ion beams: Performance and safety characteristics, and preliminary tests. Physica medica 76, 307 - 316 (2020) DOI:10.1016/j.ejmp.2020.07.0295

3. Research of the Compressed Baryonic Matter departments

Coordination: Prof. Dr. Joachim Stroth, Johann Wolfgang Goethe-Universität Frankfurt & GSI
Author: Joachim Stroth

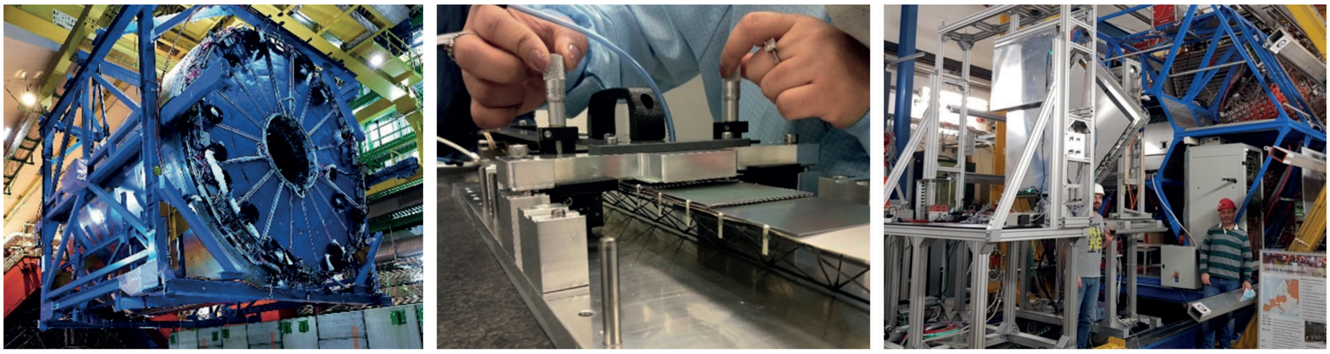


Figure 24. (from left to right) The ALICE TPC hanging on the crane in the ALICE experimental cavern pit (photograph by C. Lippmann), STS ladder assembly and a view of the new HADES Forward Detectors.

Despite the obstacles imposed by the pandemic, all departments were able to follow up their projects successfully. The shell construction at the FAIR site continued without significant delay. By the time this report has been published (September 2021) the roof of the CBM cave was already prepared for pouring concrete. This is very motivating and justifies the strong commitment of the CBM department, together with its collaborating institutes around the world, to pursue the construction of the CBM detectors using most efficiently all resources available. 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 detector system provides the platform by combining prototype or FOS detector modules with respective electronic components. The setup has been operational whenever beam from SIS18 could be delivered to the dedicated cave, which is providing sufficient shielding for runs with high-intensity beam. Equally remarkable is the timely completion of the ALICE TPC which was brought back in measurement position in August 2020. The TPC has been equipped with GEM-based readout chambers and fast electronics to provide operation without requiring a gating grid and enabling interaction rates of up to 50 kHz. In a joint effort of PANDA and HADES the instrumentation of the forward hemisphere of the HADES spectrometer was completed in time for a first commissioning run in February 2021. It is now possible to track forward going charged particles, in the region without magnetic field, in two stations of PANDA straw trackers (JU Krakow, FZJ/TransFAIR) and to measure their flight times with high precision with a new RPC wall provided by our partners from Coimbra.

In parallel to the effort devoted to the instrumentation also the analysis activities were in full swing. While ALICE is looking into the high-statistics data harvested in runs at maximum LHC energy, HADES has been busy with the 15 B events collected in 2019 for the collision system Ag+Ag at a collision energy of $\sqrt{s}$=2.54 GeV. These two data sets, respectively, mark the two extremes currently accessible via heavy-ion collisions in the exploration of the QCD phase structure of QCD and properties of QCD matter under extreme conditions. While ALICE studies matter at vanishing net-baryon density and highest initial energy density, reflecting the situation in the early universe, HADES investigates maximum net-baryon freeze-out density resembling the situation in neutron star mergers. In both cases the GSI departments crucially contribute to the analysis efforts with their expertise in handling large data sets, in tracking and detector performance simulation. An important outcome of such activities is also the common work of the CBM departments and IT department in the development of a common online-offline framework to be used in the upcoming Run 3 at LHC and later also at FAIR. Important publications have come out as addressed in the sections below.

The huge expertise of the groups in instrumentation and analysis is also the reason for strong cooperation with non-FAIR collaborations like e.g. BM@N, which is pursuing fixed-target experiments at the JINR'S Nuclotron. Synergy projects in this context receive substantial extra funds and enable state-of-the-art experiments at both facilities. Another example is the approval of a joint proposal of GSI and the nearby Hesse universities in the context of the HESSE Excellence Initiative LOEWE. ELEMENTS aims at a coherent approach of various fields of strong-interaction and atomic physics, together with accelerator science, to unravel the processes responsible for heavy element production in the universe. An important element of ELEMENTS is a strengthening of the cooperation with observers. Other examples of cooperation are joint initiatives, across the traditional boarders of particle and nuclear physics, in the field of detector technology, artificial intelligence and large-data management. These activities base on a very close cooperation between the three research departments with the Detector Laboratory and the Experiment Electronics Department of GSI. The work conducted here paves the way to future upgrades of the detectors and will guarantee forefront research also in years from now.

3.1 Department ALICE at GSI

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

The general goal of heavy-ion research is the advancement of the understanding of the strong force and of extended strongly interacting systems. Experiments with relativistic nucleus-nucleus collisions allow for a detailed characterization of the dynamic properties of matter at high energy density. A regime of high temperature and nearly vanishing net-baryon density is accessible in nuclear collisions at unprecedentedly high energies as provided by the Large Hadron Collider (LHC) at CERN, where ALICE is the flagship experiment for the characterization of the quark-gluon plasma (QGP), a state of de-confined and thermalized strongly interacting matter.

The ALICE department at GSI plays a leading role since many years in most aspects of the ALICE experiment. 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. Key contributions to the processing of ALICE data, from reconstruction to physics analysis, are in the hands of GSI, in a joint effort of the ALICE group and the scientific computing department. Furthermore, GSI group members hold key positions in the scientific coordination and in the management of the experiment.

Highlights in 2020

Scientific results

The second experimental campaign of the LHC ended in December 2018. An integrated luminosity exceeding the goal of 1 nb^{-1} was recorded for collisions of lead nuclei at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}}$ = 5.02 TeV. This is the largest data sample of the highest energy nuclear collisions that ever became available for physics analysis. A significant fraction of the year 2019 was used for the calibration, reconstruction and optimization of this unique data set for the physics analysis, which is in full swing ever since. The ALICE team at GSI is leading the analysis related to a number of observables that are crucial for shedding further light on the properties of the QGP produced in heavy-ion collisions at the LHC. This is reflected in the strong contributions of GSI to the physics output of the ALICE Collaboration in 2020.

One focus of the ALICE-GSI group is the investigation of collective flow in heavy-ion collisions, which is addressed via measurements of hadrons not only carrying the light up, down, and strange quarks, but also the heavy charm and beauty quarks.

In the light-flavor sector, the production of loosely bound light nuclei, hyper-nuclei, and their corresponding anti-nuclei is of particular interest. The production mechanism of these nuclei is still not understood. Elucidating these 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 accounts for a large fraction of matter in our universe. A first measurement of the collective elliptic flow of (anti-)^{3}He nuclei [1], one highlight of the physics analysis in the ALICE-GSI group in 2020, provides new experimental constraints on the production mechanisms of light (anti-)nuclei.

In the heavy-flavor flow sector, another particular highlight in 2020 was the first measurement of a large charge-dependent directed flow of charm hadrons in Pb-Pb collisions at the LHC [2]. Charm is produced at ultra-relativistic energies in the form of quark-antiquark pairs in hard scattering processes in the initial stage of the collision, at a time when the electromagnetic fields generated by the lead nuclei passing each other at nearly the speed of light are still large. This is in contrast to light-flavor hadrons which originate mostly from thermal production in the QGP, a phase in the collision process at which the initial electromagnetic fields do not play a relevant role anymore.

In addition to the physics of open heavy-flavor hadrons, another priority of the ALICE-GSI group is the investigation of the production of charmonia, i.e. bound states of charm quarks and antiquarks. These are sensitive to de-confinement and can give insight into the phase structure of strongly interacting matter. A highlight of 2020 is a measurement of the centrality and transverse-momentum dependence of inclusive J/ψ production at midrapidity in Pb-Pb collisions [3], which underlines the importance of the (re)generation of charmonia from a de-confined QGP.

Figure 25. The ALICE Time Projection Chamber, after successful installation and pre-commissioning of the new GEM readout chambers, is transported back to ALICE (photograph: CERN).

ALICE upgrades

The ALICE group at GSI has a central role in the upgrade of the ALICE Time Projection Camber TPC and in the realization of the new Online-Offline facility and software framework (the O^2 project).

In the course of 2019, the TPC was removed from its position inside the experiment and installed in a clean room on the surface, where the original multi-wire proportional chambers were replaced by the newly built readout chambers equipped with Gas Electron Multiplier foils (GEMs). The first half of the year 2020 was dedicated to a very intense pre-commissioning campaign in the clean room. Cosmic rays, laser and pulser signals, and the radiation from a strong X-ray source were used to test the entire system.

After this extensive test phase, in August 2020 the TPC was extracted from the clean room and transported back to ALICE (Figure 25), where it was lowered into the ALICE cavern (Figure 26, left panel) and brought close to its final position inside the ALICE magnet (Figure 26, right panel). The cabling and careful alignment of the TPC to the nominal position around the LHC interaction point were completed in October 2020. Since then, thorough tests of the entire system and further commissioning with X-rays are ongoing. The ALICE TPC is fully back to life and has been recording cosmic data regularly since then.

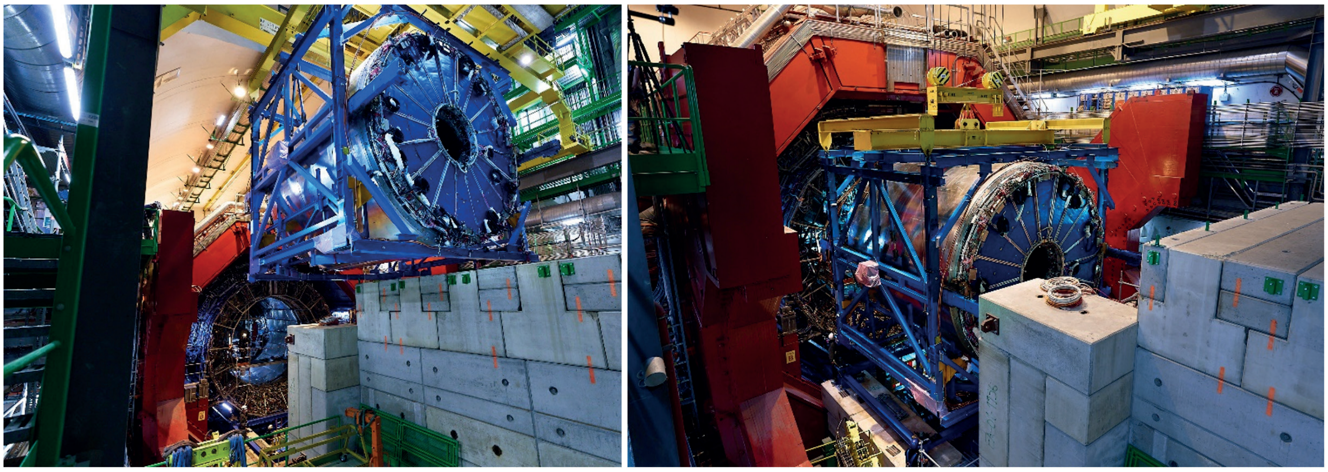


Figure 26. The TPC is lowered into the ALICE cavern (left panel) and inserted into the ALICE mainframe (right panel), on the way towards its nominal position at the heart of the experiment (photographs: CERN).

As a consequence of the Covid pandemic, the LHC schedule has been revised. The ongoing Long Shutdown 2 has been prolonged until early 2022: the experimental caverns will be closed on February 1, 2022, to prepare for the restart of physics data taking in May.

The installation and continuous commissioning of the TPC in 2020 has been a great success and promises a new, long physics season at the LHC with its Runs 3 and 4, until the end of this decade. To prepare for that, efforts are concentrated on the development of the software needed for the calibration and reconstruction of the data from the upgraded detector.

Outlook for 2021

In 2021, the installation of all upgraded detectors in ALICE will be completed in late spring. From June onward the global commissioning of the experiment will take place, to prepare for a pilot run of the LHC in September 2021: for a few hours, the LHC beams will be brought to collision, and ALICE will record data for an important commissioning of the data flow, the calibration and reconstruction procedures.

In the meanwhile, the ALICE team at GSI will concentrate its other efforts on the full exploitation of the data recorded until 2018 with physics analyses relevant for the focal topics in the group.

Selected publications of 2020

- [1] Acharya, S. ; Adamova, D. ; Adhya, S. P. ; et al (ALICE Collaboration): Measurement of the (anti-)^{3}He elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02TeV. Physics letters / B 805, 135414 (2020), DOI:10.1016/j.physletb.2020.135414
- [2] Acharya, S. ; Adamova, D. ; Adler, A. ; et al (ALICE Collaboration): Probing the effects of strong electromagnetic fields with charge-dependent directed flow in Pb-Pb collisions at the LHC. Physical review letters 125(2), 022301 (2020), DOI:10.1103/PhysRevLett.125.022301
- [3] Acharya, S. ; Adamova, D. ; Adler, A. ; et al (ALICE Collaboration): Centrality and transverse momentum dependence of inclusive J/ψ production at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV. Physics letters / B 805, 135434 (2020), DOI:10.1016/j.physletb.2020.135434

3.2 Department CBM at FAIR

Head: Prof. Hans Rudolf Schmidt, Eberhard Karls Universität Tübingen & GSI
Author: Olga Bertini, Johann Heuser, Hans Rudolf Schmidt

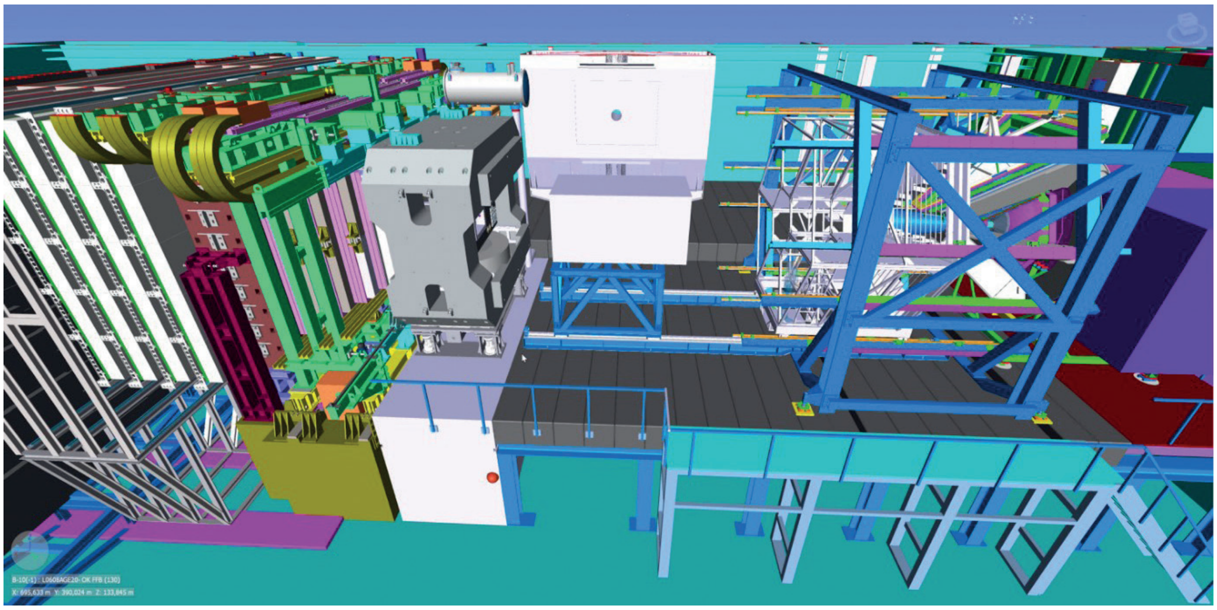


Figure 27. Sideview of the CBM Experiment at FAIR.

The CBM Experiment

As the CBM cave on the FAIR site progresses to completion in 2023/24, the design of the CBM experiment and in particular the cave and experimental infrastructure is taking shape. Shown is a side view of the CBM experiment including the HADES setup on the right on the so-called upstream platform (see Figure 27). On the left is the magnet that houses the silicon tracker (not visible), followed by the RICH detector, the transition radiation detector and the time-of-flight layers. All detector components have their support structures and supply lines integrated into the setup.

STS Modules and Ladders

The smallest functional unit of the Silicon Tracking System, the module, is an assembly of a double-sided silicon micro-strip sensor, bonded to ultra-low mass read-out cables, and front-end electronics for high-rate charge and time measurement of registered particles. The STS detector system will comprise a total of 897 modules in multiple variants. Up to 10 modules will be installed on a detector ladder, the basic mechanical structure, made from low-mass carbon fiber material. Altogether, 106 ladders will be deployed on the detector systems' tracking stations.

In 2020, module and ladder assembly has been advanced towards starting pre-series production of those objects in the second half of 2021. All components have been developed and are either already available in full amount (as the silicon sensors and the carbon fiber structures produced in industry), or in a pilot-batch (as the STS-XYTER read-out ASIC and the micro-cables) prior to their series production in micro-electronics industry. All in-going components and interim assemblies are quality assured and tested for functionality, as the final object cannot be reworked. The silicon sensors, already certified by the vendor, undergo an additional extended electrical and optical inspection at GSI upon reception. The ASICs have a full quality screening before further integration with micro-cables.

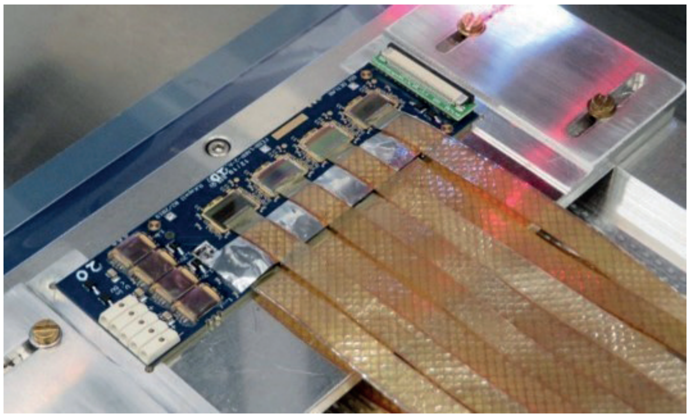


Figure 28. Module assembly: Micro-cables tab-bonded to the read-out ASICs which mounted on a front-end readout board.

Using custom-developed tooling for the two-sided handling of the components during tab-bonding at the module assembly sites GSI, KIT and JINR, the chip-cables are bonded onto the front-end electronics boards (cf. Figure 28) and then finally onto the silicon sensors.

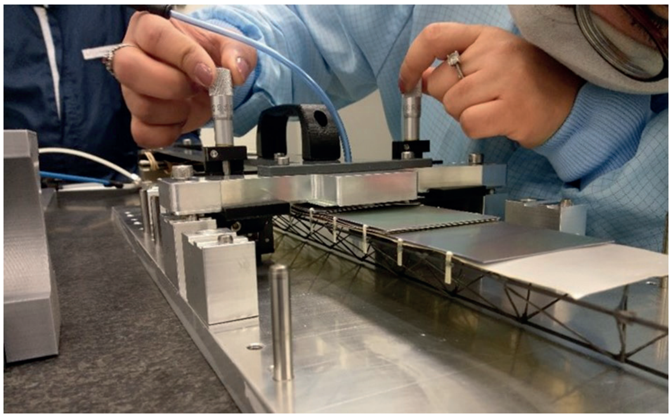


Figure 29. Ladder assembly: Precision tooling for the installation of silicon sensor modules onto a carbon fiber support.

Ladder assembly starts from the carbon fiber spaceframe. In a precision mechanical fixture, the frame is then fitted with bearings on either side which define the ladder mounting points to the detector's mechanical half units. In a number of further steps, this fixture is also utilized to attach miniature mounting legs to the carbon fiber structure, onto which the sensors of the modules to installed will be fixed with flexible glue. Step by step, one module after the other, up to five modules in one half of a full ladder, and another five to the other half, is lowered down to the structure with further specific tools as shown in Figure 29.

Sensor Quality Control

Serial production of silicon sensors for the STS was completed in 2020. Nearly 1200 sensors were delivered at GSI and underwent rigorous quality control (QC). The first step of QC was optical inspection (OI) of the sensor surface. A variety of defects, such as implant breakage, p-stop breakage, aluminum shorts and openings, and their clusters, were identified using the Convolutional Neural Network object recognition approach. It was used to determine the quality level of the sensor. The sensors were then tested for their current-voltage and capacitance-voltage characteristics. Detailed investigation of the sensor I-V characteristics is required due to the intended placement of the sensors in a high radiation environment, where depletion voltages well in excess of 120 V, as guaranteed by the manufacturer, are required. All sensors have been tested to see if a maximum reverse bias voltage (500V) can be applied. As an example, the I-V characteristic is shown in Figure 30 for the small, i.e., 2 x 6 cm^2 sensors. These sensors are located at forward angles and require depletion voltages beyond 120 V due to radiation damage. In addition, an overall quality score is calculated from all available information: optical inspection, basic electrical inspection, strip test, and manufacturer data. The available inspection results allow us to conclude that we have obtained a sufficient number of good quality sensors to use in the STS detector.

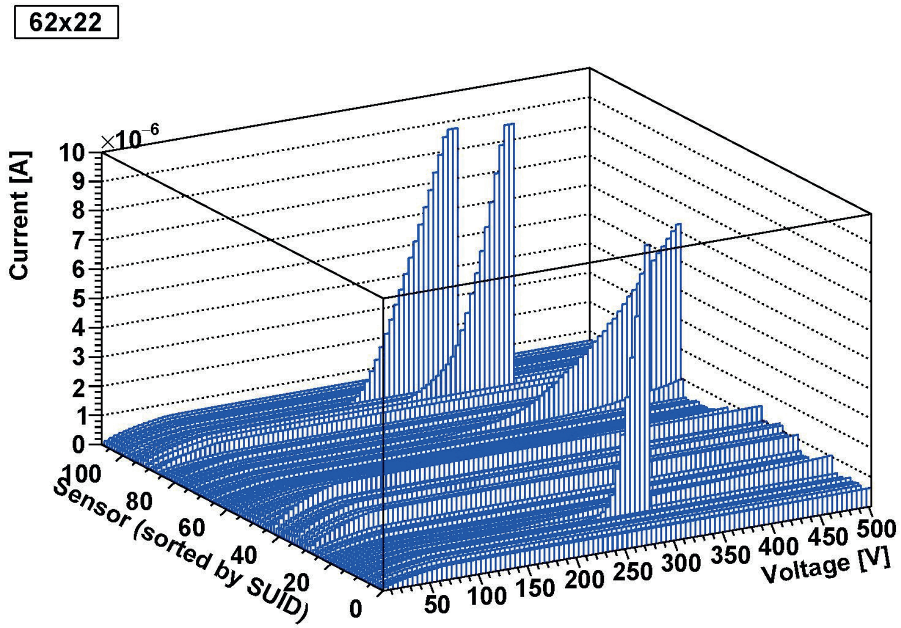


Figure 30. Summary of the I-V scans for the 2 x 6 cm^2 sensors, which will be placed at small angles.

3.3 Department HADES

Prof. Dr. Joachim Stroth Goethe University Frankfurt am Main & GSI
Authors: Joachim Stroth

HADES analysis activities 2020

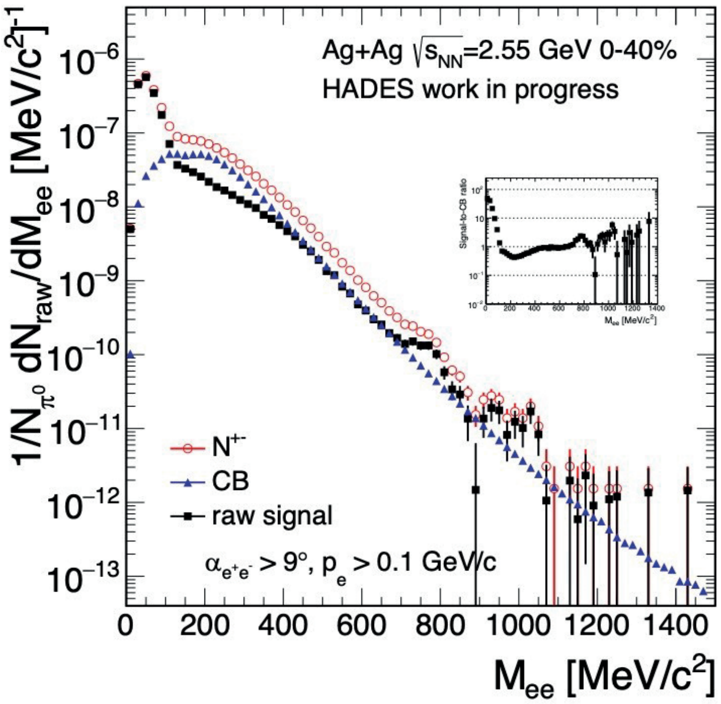


Figure 31. Raw (i.e. not efficiency corrected) dielectron invariant-mass distributions obtained from the 40% most central Ag+Ag collisions at = √(s_{NN})2.55 GeV. Red circles: all same-event unlike-sign combinations (N^{+-}), blue triangles: the calculated combinatorial background (CB), black squares: the raw signal (N^{+-} - N^{CB}). The insert shows the signal-over-CB ratio versus pair invariant mass.

In 2020 we have focused on the analysis of experimental data collected in March 2019 by colliding Ag ions with an Ag target at center-of-mass energies of √(s_{NN})= 2.4 and 2.55 GeV. Thanks to the newly installed photon detector of the HADES RICH (CBM FAIR Phase-0), the electron identification efficiency could be increased by a factor three. This improvement results from a much larger single photon detection capability which also enables the discrimination of electron-positron pairs, emitted with very small opening angle, from singles just by the amount of hits making up the ring. The benefit is a significantly improved rejection of dielectrons from photon conversion and π^0 Dalitz decays. The dilepton spectrum, shown in Figure 31, is obtained by subtracting from the differential pair yield (dN^{+-}/dM_{ee}) the contribution due to combinatorial background (CB) estimated using same-event like-sign combinations and event-mixing. Also depicted is the signal-to-background ratio, which reaches unity already at 400 MeV/c^2 invariant mass and up to five in the vector-meson region. The number of signal pairs above the π^0 Dalitz region is 160.000 and 16.000 for √(s_{NN})= 2.55 and 2.42 GeV, respectively.

Regarding the investigation of hadronic probes, the analysis of the data from the 2012 Au+Au experiment are close to being finalized. In particular, nuclear cluster production (d, t, He) has been investigated, a very comprehensive multi-order flow analysis has been finished, and the influence of Coulomb effects on charged pion spectra has been scrutinized. Final results on two-pion intensity interferometry are summarized in Eur. Phys. J. A 56, 140 (2020). A systematic study of the anisotropic flow of protons, deuterons and tritons has been documented in Phys. Rev. Lett. 125, 262301 (2020). Here, for the first time, also higher-order flow coefficients were determined for collisions in this energy region, which allowed to reconstruct the complete angular emission pattern for protons (see Figure 32). A publication on flow measurements for pions and kaons in Au+Au collisions is currently under preparation.

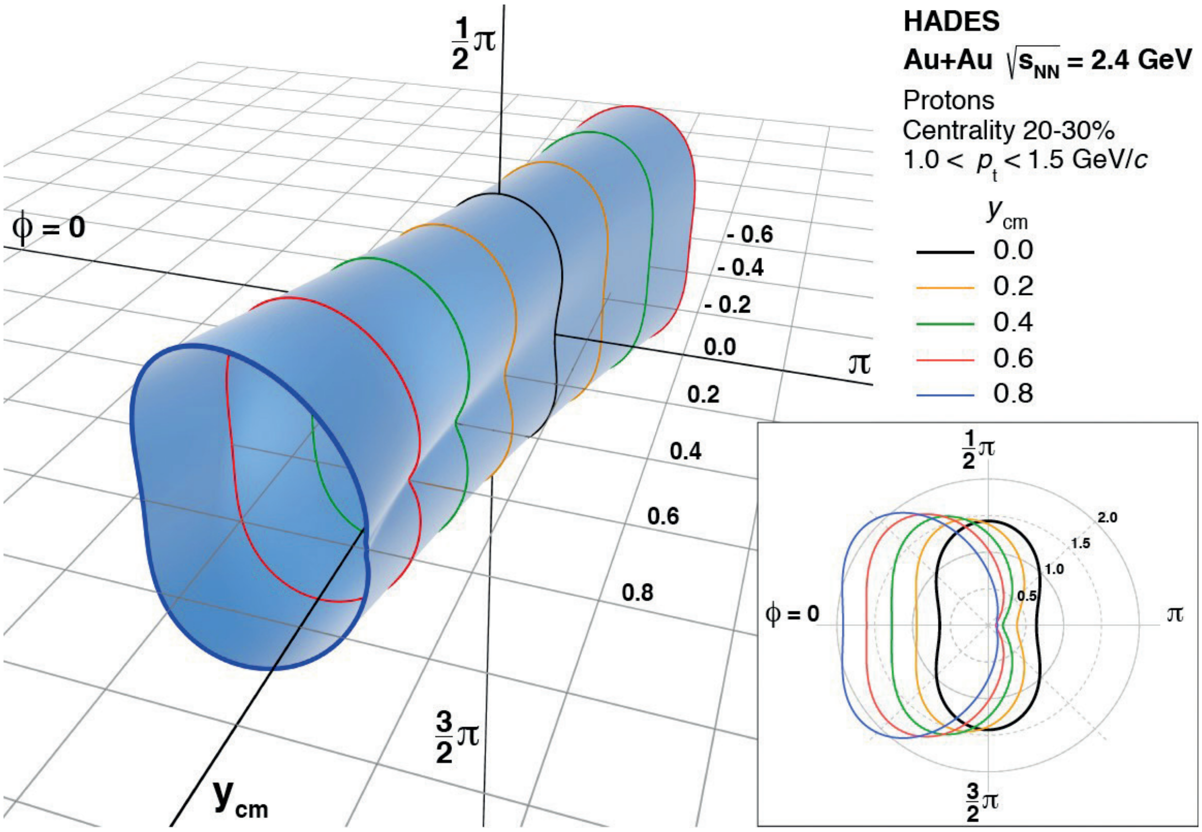


Figure 32. Multi-order proton flow pattern measured in 1.23 AGeV Au+Au collisions.

The activity in the hadron working group was concentrated, however, on the analysis of the Ag+Ag data taken in 2019. During the year, a special focus was put on the reconstruction of hadrons carrying strangeness via their weak decay products. Such events have a characteristic decay topology, which can be used to suppress combinatorial background at the price of a reduced reconstruction efficiency. We use machine-learning methods based on artificial neural networks in order to mitigate the loss in efficiency. Such algorithms can be trained to recognize specific correlations and are commonly used for identification of charged particles passing through the detector, resulting in higher reconstruction efficiencies compared to any combination of orthogonal hard cuts. This method has been proven to be quite successful and it allowed to reconstruct K^0 and Λ phase-space distributions with high accuracy. In addition, a hypertriton signal could be reconstructed in the $^3H_\Lambda$ -> ^{3}He + π^- decay channel. The corresponding invariant-mass distribution of ^{3}He and π^- pairs, displayed in Figure 33, shows a significant hypertriton peak above the combinatorial background estimated with the mixed-event method. From these data, the phase space distribution of the $^3H_\Lambda$ as well as its lifetime can be determined.

Furthermore, in 2020, several correlation analysis projects involving the Ag+Ag data of 2019 have been pursued. These include studies of the directed and elliptic flow of protons and Λ hyperons, as well as an investigation of the global Λ polarization. The latter is sensitive to a global spin polarization of the produced particles, induced by the extremely high orbital angular momenta generated in non-central heavy-ion collisions. A preliminary study of Ag+Ag and Au+Au collisions results in the highest up-to-now observed global Λ polarization values of 3 – 5%. Furthermore, femtoscopic analyses using two-pion and proton-Λ pair correlations have been started for the Ag+Ag data.

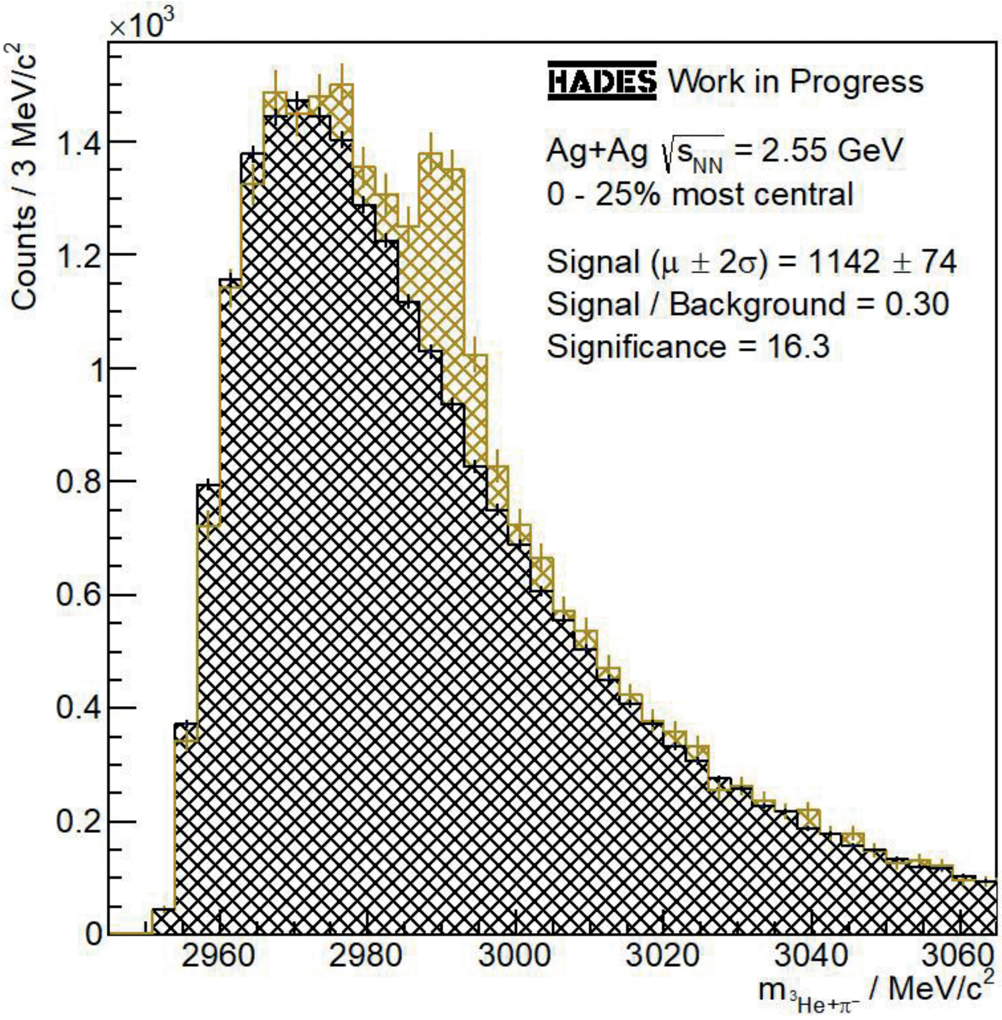


Figure 33. Invariant-mass distribution of ^{3}He – π^- pairs. The same-event spectrum (yellow) shows a significant peak above the combinatorial background and is attributed to hypertriton production. The CB is obtained from event mixing.

Spectrometer upgrade

In the coming years of the FAIR Phase-0 program HADES has planned several runs with focus on exclusive reconstruction of resonance and hyperon production. In particular, in combination with the excellent dielectron detection capability of HADES, electromagnetic transition form factors (eTFF) of resonances and hyperons are addressed. The program on hyperon eTFF is in collaboration with PANDA. In that context, the instrumentation of the very forward hemisphere of the detector has been almost completed. By the end of 2020, two tracking stations based on PANDA Straw Tracker Station (STS) technology have been installed. For time-of-flight measurement with high precision, a RPC station has been developed in addition, and one half of the detector already mounted. Also foreseen for such runs is a new, low granularity, time-of-flight detector with low material budget. It is placed in front of the inner drift-chamber system to enhance the trigger purity. Other upgrade projects concern in beam detectors based on LGAD technology and the replacement of the 20-years old MDC front-end electronics. First prototype boards implementing the PANDA PASTTREC read-out chips and a FPGAs are produced and being tested.

Outlook for 2021

2021 we see first publications of results from the Ag+Ag experiment. We will launch a detailed comparison of the obtained Au+Au and Ag+Ag data with results from microscopic transport theory calculations. We also plan to repeat the analysis on event-by-event fluctuations of proton multiplicities based on the Bayesian particle identification for Au+Au and also for the Ag+Ag data.

A short test beam with the new detector systems in place had already been carried out while this report was written. The data will be used to prepare preliminary calibrations and to train the reconstruction software to be prepared for the production run on hyperon production in p+p collisions planned for February 2022.

Selected publications in 2020

- [1] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al: Directed, Elliptic, and Higher Order Flow Harmonics of Protons, Deuterons, and Tritons in Au + Au Collisions at $\sqrt{s_{NN}}$ = 2.4 GeV. Physical review letters 125(26), 262301 (2020), DOI:10.1103/PhysRevLett.125.262301
- [2] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al: Identical pion intensity interferometry at $\sqrt{s_{NN}}$=2.4 GeV. The European physical journal / A 56(5), 140 (2020), DOI:10.1140/epja/s10050-020-00116-w
- [3] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al: Proton-number fluctuations in $\sqrt{s_{NN}}$ =2.4 GeV Au + Au collisions studied with the High-Acceptance DiElectron Spectrometer (HADES). Physical review / C 102(2), 024914 (2020), DOI:10.1103/PhysRevC.102.024914
- [4] Adamczewski-Musch, J. ; Arnold, O. ; Atomssa, E. T. ; et al: Two-pion production in the second resonance region in π^-p collisions with the High-Acceptance Di-Electron Spectrometer (HADES). Physical review / C 102(2), 024001 (2020), DOI:10.1103/PhysRevC.102.024001
- [5] Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al: Charged-pion production in Au+Au collisions at $\sqrt{s_{NN}}$=2.4 GeV. The European physical journal / A 56(10), 259 (2020), DOI:10.1140/epja/s10050-020-00237-2

4. Research of the NUSTAR departments

Coordination: Prof. Dr. Christoph Scheidenberger, Justus-Liebig-Universität Gießen & GSI
Author: Christoph Scheidenberger

Figure 34. Participants of the NUSTAR Annual Meeting 2020. Despite the advent of practical restrictions due to the covid-19 pandemic, many participants attended the NUSTAR Annual Meeting in the week 2-6 March 2020. The various NUSTAR sub-collaborations presented their views and plans for the FAIR Phase-0 program. Presently, the NUSTAR Collaboration has more than 700 registered members from more than 135 institutions in 33 countries. The NUSTAR strategy aims at the exploitation of new opportunities at the existing facilities and a continuous transition from GSI to FAIR as soon as the Super-FRS will be available. (Photograph: G. Otto, GSI)

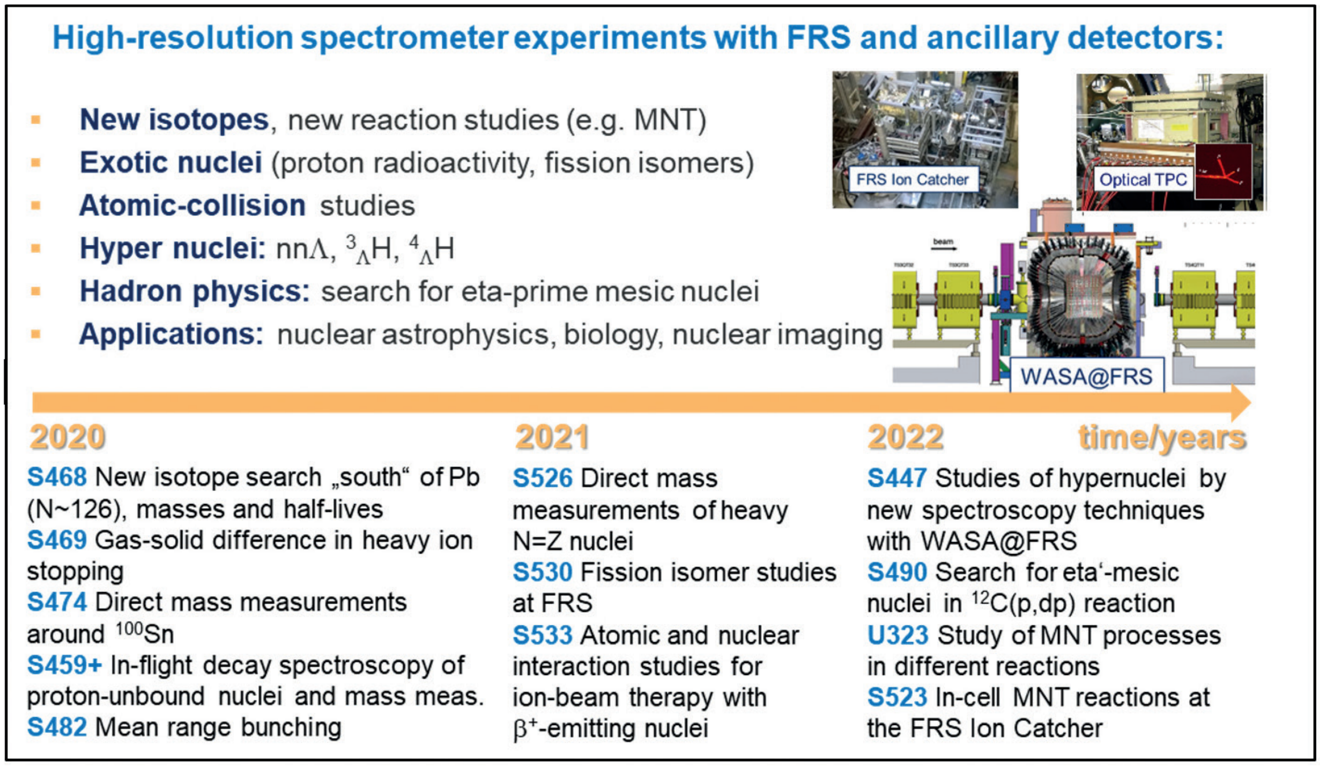
The NUSTAR Collaboration is one of the four major collaborations that are conducting scientific research at GSI and FAIR. The NUSTAR departments of GSI and HIM (Helmholtz Institute Mainz) are integral part of the NUSTAR Collaboration and participate in and contribute to the experiments with intense stable 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 a world-leading research program addressing nuclear structure far-off stability, nuclear astrophysics, reaction studies with exotic nuclei, and physics and chemistry of superheavy elements.

The year 2020 was very busy due to the continuation of a vivid experiment program at the UNILAC and FAIR Phase-0 experiments at SIS18. Despite the prevailing pandemic, the experiments could be performed almost according to the originally intended schedule; however, travel and participation of collaborators from abroad was severely restricted; this prompted the ad-hoc implementation of many different measures for 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 was really excellent. The efforts aimed at the commissioning with beams, optimization and exploitation of the new equipment and algorithms (including new technologies like machine learning and artificial intelligence) and the performance of the approved FAIR Phase-0 experiments. It allows 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 PhD students and young post-docs on the way to NUSTAR@FAIR. The first results are displayed in the following sections.

Figure 35. In the framework of the Annual Meeting 2020, the FAIR-GENCO Award for Young Scientists was handed over. The prize is awarded by the GSI Exotic Nuclei Community (GENCO) in honor of the lifetime achievements of its founding father Gottfried Münzenberg (third person from the left). This year's award went to Dr. Clémentine Santamaria from the Lawrence Berkeley National Laboratory (USA) for her milestone exploration to answer long-standing questions of the evolution of nuclear shell structure far from stability and her striking expertise in both nuclear spectroscopy and nuclear reactions. The photograph shows also several new members of GENCO. (Photograph: G. Otto, GSI)

4.1 Department FRS/SFRS Experiments

Head: Prof. Dr. Christoph Scheidenberger, Justus-Liebig-Universität Gießen & GSI
Author: V. Chudoba (Univ. Opava), T. Dickel, A. Fomichev (JINR-Dubna), B. Franczak, H. Geissel (GSI, JLU-Gießen), E. Haettner, C. Hornung, D. Kostyleva, N. Kuzminchuk, I. Mukha, W. R. Plaß (GSI & JLU-Gießen), S. Purushothaman, T. Saito (GSI & RIKEN), C. Scheidenberger (GSI & JLU-Gießen), Y. Tanaka (RIKEN)



High-resolution spectrometer experiments with FRS and ancillary detectors:

- **New isotopes**, new reaction studies (e.g. MNT)
- **Exotic nuclei** (proton radioactivity, fission isomers)
- **Atomic-collision** studies
- **Hyper nuclei:** nnΛ, $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$
- **Hadron physics:** search for eta-prime mesic nuclei
- **Applications:** nuclear astrophysics, biology, nuclear imaging

2020

S468 New isotope search „south" of Pb (N~126), masses and half-lives
S469 Gas-solid difference in heavy ion stopping
S474 Direct mass measurements around ^{100}Sn
S459+ In-flight decay spectroscopy of proton-unbound nuclei and mass meas.
S482 Mean range bunching

2021

S526 Direct mass measurements of heavy N=Z nuclei
S530 Fission isomer studies at FRS
S533 Atomic and nuclear interaction studies for ion-beam therapy with β^+-emitting nuclei

2022

S447 Studies of hypernuclei by new spectroscopy techniques with WASA@FRS
S490 Search for eta'-mesic nuclei in ^{12}C(p,dp) reaction
U323 Study of MNT processes in different reactions
S523 In-cell MNT reactions at the FRS Ion Catcher

Figure 36. Overview of scientific program, physics goals and pilot experiments in years 2020-2022 of the Super-FRS Experiment Collaboration.

The department members pursue research activities in the framework of the Super-FRS Experiment Collaboration within NUSTAR. They use the FRS at GSI and aim at using in future the Super-FRS at FAIR as high-resolution momentum spectrometer together with ancillary detectors (like the FRS Ion Catcher, EXPERT, WASA, and others) for experiments with stable and exotic nuclei. The physics program and mid-term plans are depicted in Figure 36. The experiments planned for 2020 (as outlined in Figure 36) have been performed. The data analysis has started.

The FRS/SFRS department also maintains and runs – with the dedicated support of the Super-FRS project group and the Super-FRS Experiment Collaboration – the FRS for all experiments of the NUSTAR Collaboration with exotic nuclei at SIS18. After refurbishment of the FRS Standard Equipment in years 2017-2019 and the successful commissioning of the FRS controls in the new FAIR software environment LSA, a large number of experiments could be performed (eleven in total) in the first half of 2020, all in all some 169 shifts, despite the pandemic and related restrictions, and strongly assisted by many collaborators worldwide, who participated remotely. Some results are described in the following sections.

Highlights in 2020

A new branch of the FRS: radioactive beams for bio-medical applications and related basic studies

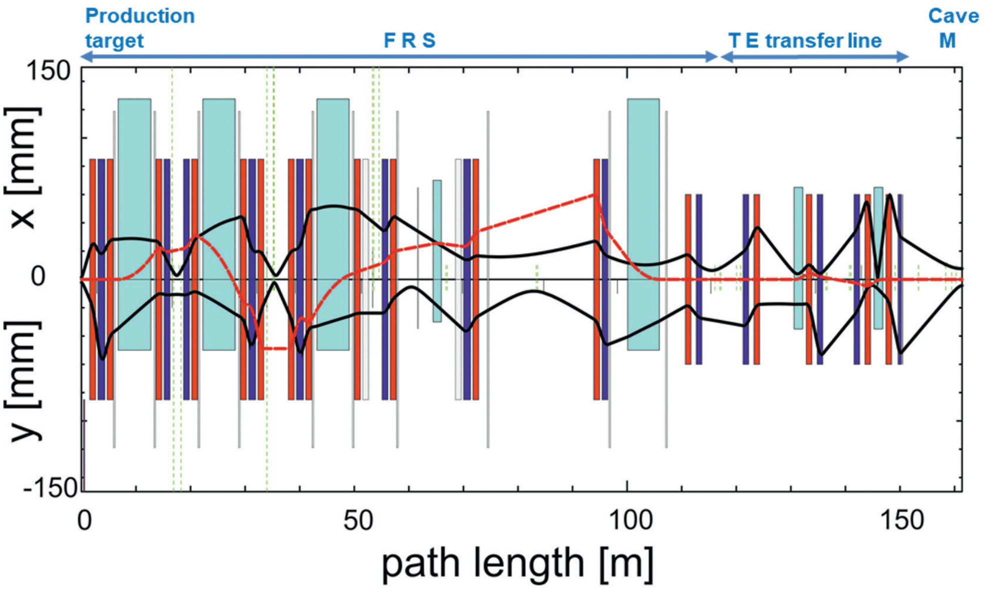


Figure 37. Ion-optical mode of the FRS for the separation of light positron-emitting nuclei and their efficient transport via the primary-beam line to Cave M. The separator is achromatic and the beam transport line is also achromatic. The beam envelopes (solid black lines) are MIRKO calculation results for horizontal and vertical emittances of 20 π mm mrad, the dashed red line is the dispersion line for +1 % momentum deviation.

Triggered by the success of tumour treatment with relativistic heavy ions (such as ^{12}C or ^{16}O), the possibility of using radioactive beams for particle therapy and related medical applications has attracted large attention in recent years. Short-lived positron-emitting species (such as ^{11}C or ^{15}O) have similar biological effects, but may offer several advantages with respect to online dosimetry and in-situ imaging. The Super-FRS Experiment Collaboration and the FRS/SFRS group will play a key role in this activity and will study the basics of radioisotope production, investigate accurately their atomic and nuclear interactions with matter and contribute to the improved PET studies with radioactive beams at GSI. For these studies and for efficient transport of the PET-isotopes to Cave M a new ion-optical mode has been developed, which is depicted in Figure 37. It 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, whose design is adapted to the small emittances of primary beams from SIS18.

Direct mass measurements with the FRS Ion Catcher

The FRS Ion Catcher is a setup at the final focal plane of the main branch of the fragment separator FRS for precision experiments with thermalized exotic nuclei, which are produced by projectile fragmentation or fission. The fragments are produced at relativistic energies, separated in-flight and energy-bunched in the FRS. At the FRS Ion Catcher, these fragments are then slowed down and thermalized in a Cryogenic Stopping Cell (CSC). A Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) is used to perform direct mass measurements. A versatile RF quadrupole transport and diagnostics unit guides the ions from the CSC to the MR-TOF-MS, provides differential pumping, ion identification, mass separation, and includes reference ion sources. The FRS Ion Catcher serves as a test facility for the Low-Energy Branch of the Super-FRS and already now enables a large variety of experiments.

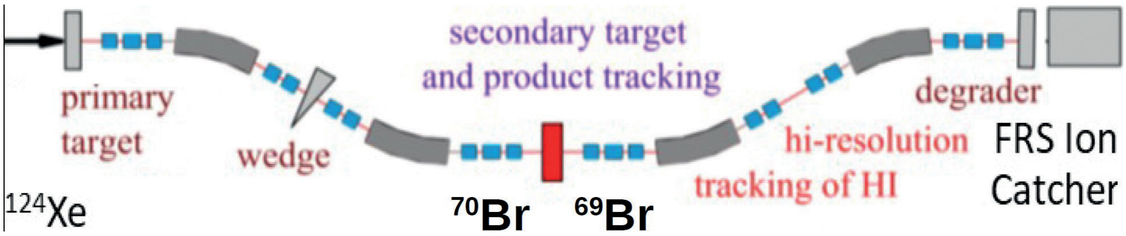


Figure 38. Scheme of the experiment performed in 2020, which combines EXPERT detectors and FRS Ion Catcher and which efficiently makes double use of the secondary beams, which were produced by fragmentation of a 980 MeV/u ^{124}Xe primary beam.

In 2020, four experiments involving the FRS Ion Catcher have been performed in the context of FAIR Phase-0, experiment S474, "Detector tests with the prototype CSC for the Super-FRS and direct mass measurements of neutron-deficient nuclides below ^{100}Sn", experiment S459, "A combined experiment (see Figure 38) of the proposals of EXPERT (S443, S459) and the FRS Ion Catcher (S472), "Focused on Br isotopes at and beyond the proton dripline", experiment S468, "Search for new neutron-rich isotopes and exploratory studies in the element range from terbium to rhenium", and experiment S482, "Mean range bunching for experiments with stopped beams".

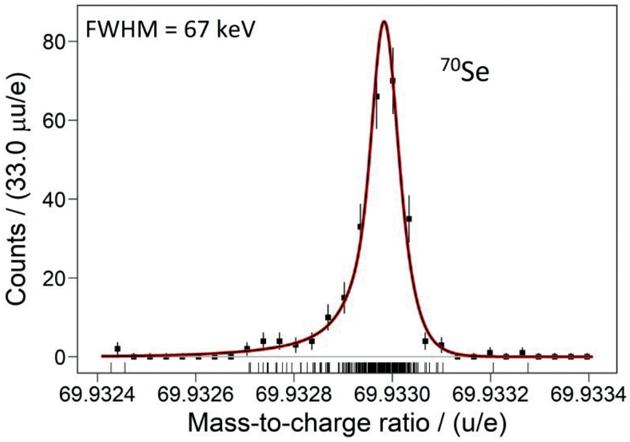


Figure 39. Mass spectrum of ^{70}Se measured with the FRS Ion Catcher. A Hyper-EMG function with a FWHM of 67 keV, corresponding to a mass resolving power of m/Δm=970,000) was used for fitting the unbinned data.

Among others, mass measurements of As, Se and Br isotopes in the vicinity of the N=Z line were performed. An unprecedented mass resolving power for MR-TOF-MS of almost 1,000,000 was achieved (see Figure 39), leading to relative mass uncertainties of short-lived rare isotopes that are as good as 10^{-7} with less than 10 detected events and 10^{-8} with merely a few hundred events. Such performance places the MR-TOF-MS at the level of Penning traps, the 'gold-standard' of atomic mass spectrometry, however with much shorter cycle time and much larger mass range. The high resolving power is the only way to achieve accurate results and resolve overlapping peaks of short-lived exotic nuclei, whose total number of accumulated events is always limited.

The results show that the measured re-strengthening of the proton-neutron interaction for odd-odd nuclei along the N=Z line above atomic number Z=29 (recently extended to Z=37) is hardly evident at the N-Z=2 line, and not evident at the N-Z=4 line. This indicates that this re-strengthening is a unique feature of medium-mass N=Z nuclei, and is counter-intuitive since first principles suggest the decrease of the proton-neutron interaction strength with nuclear mass. On the other hand, the detailed structure of the proton-neutron interaction along the N-Z=2 and N-Z=4 lines, confirmed by the mass measurements, may provide a hint regarding the ongoing ≈500 keV discrepancy in the mass value of the N=Z nuclide ^{70}Br, which prevents including the ^{70}Br mass in the world average of Ft value for super-allowed 0+ -> 0+ β-decays.

The reported work sets the stage for mass measurements with the FRS Ion Catcher of medium-mass nuclei at and beyond the N=Z line, including the nuclide ^{70}Br. Experiments with the FRS Ion Catcher will be continued in FAIR Phase-0 in 2021 with S530 “Fission isomer studies with the FRS” and S526 “Direct mass measurements of heavy N=Z and N=Z-1 nuclides”.

[Mar21] I. Mardor et al., Phys. Rev. C. 103 (2021) 034319.

Experiments with EXPERT prototype detectors and related developments

The EXPERT (Exotic Particle Emission and Radioactivity by Tracking) project aims at studies of exotic nuclear systems near and beyond the driplines by tracing their decay products in flight. The EXPERT experiments will use the first stage of the (Super-)FRS as separator for radioactive beams and the second stage as analyser. The unbound nuclei of interest will be produced by secondary reactions in a target located at the central focal plane of the (Super-)FRS, and the trajectories of their decay products will be tracked in order to derive their half-lives, resonance energies and other nuclear structure information.

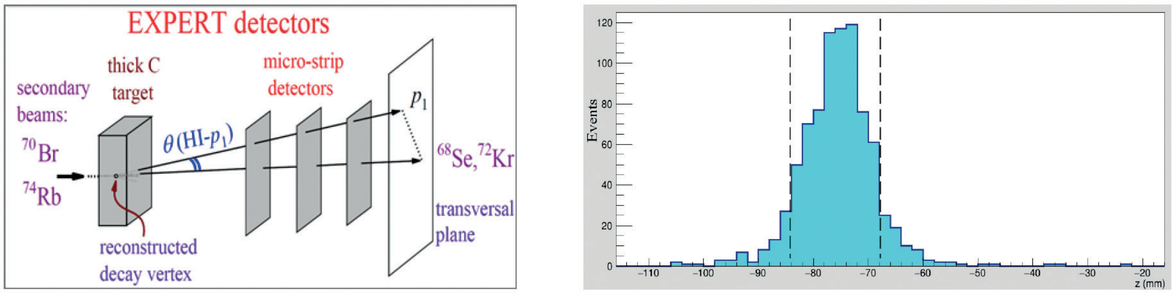


Figure 40. Scheme of the EXPERT setup located at the central focal plane of FRS. Right panel: Vertex distribution of decays ^{62}Zn*->^{58}Ni+ α in beam direction (z) as measured with Si tracking detectors; the dashed lines indicate the target front and back side of the ^{12}C target, inside which the prompt decays occur.

As mentioned before, two FAIR Phase-0 experiments of the EXPERT, S443 and S459, have been performed in combined measurements together with the FRS Ion Catcher experiment S472, where two detector setups were located at the middle and final focal planes of the FRS (see Figure 40) and several properties of exotic nuclei around or at the N=Z line (e.g., ^{70}Br and ^{74}Rb) were measured simultaneously.

New Si microstrip detectors, produced by the INFN-Perugia, were successfully tested by performing in-flight decay spectroscopy of the proton-unbound nuclei ^{69}Br and ^{73}Rb. They are of interest for the role they play in rapid proton capture processes, which drive thermonuclear type-I x-ray bursts in stars, thus facilitating the element synthesis in the Universe. In total, about 106 projectiles of ^{70}Br and ^{74}Rb impinged on the secondary ^{12}C target and produced ~80 ions of ^{69}Br and ~40 ions of ^{73}Rb, respectively. Their 1p-decays were identified and tracked, and the corresponding life times and decay energies will be derived.

The calibrations of the tracking microstrip detectors is accomplished by using the measured (as by-product) α-^{58}Ni correlations, which result from decays of excited states in ^{62}Zn. Their properties are known from ^{58}Ni(^{6}Li,d)^{62}Zn* and ^{64}Zn(p,t)^{62}Zn* reactions. In the right panel of Figure 40 the measured vertex distribution of decays ^{62}Zn*->^{58}Ni+α is presented. The angular correlations α-^{58}Ni shown in Figure 41 clearly point to the 10.3 and 13.4 MeV excited states in ^{62}Zn, which correspond to the two strongest peaks of the distribution. As so far only 5% of the available statistics have been used, the final calibrations will allow for precise spectroscopy of the isotopes of interest ^{69}Br and ^{73}Rb. The corresponding data analysis is expected to be completed in 2021. Several of the above-mentioned methods were applied recently in the common work [Bez20] at JINR in Dubna.

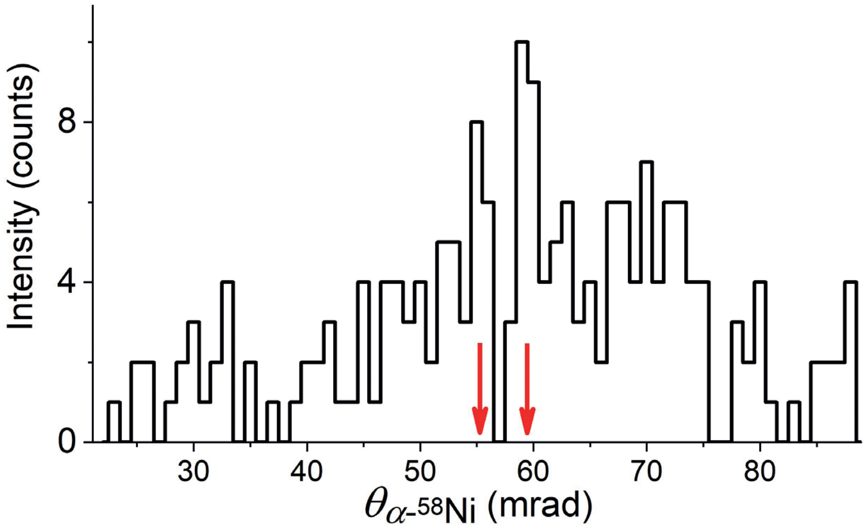


Figure 41. Histogram of angular correlations of ^{58}Ni and α-particles emitted in the decays of ^{62}Zn*. The two strongest peaks (indicated by red arrows) correspond to the known 10.3 MeV and 13.4 MeV states in ^{62}Zn.

In the forthcoming experiments, new Si microstrip detectors with large active area of 10·10 cm^2 will replace the previously used detectors for tracking of protons or α-particles and heavy ions; also new front-end boards, digitising and FPGA-based steering modules will be used. For the neutron detector NeuRad of EXPERT, which is based on scintillator fibers, a set of recently-developed 64-channel ASICs by PetSys electronics has been produced and tested and will be used in the next experiments.

[Bez20] A.A. Bezbakh, V. Chudoba et al., Phys. Rev. Lett., 124, 022502 (2020).

Preparations for experiments using WASA@FRS

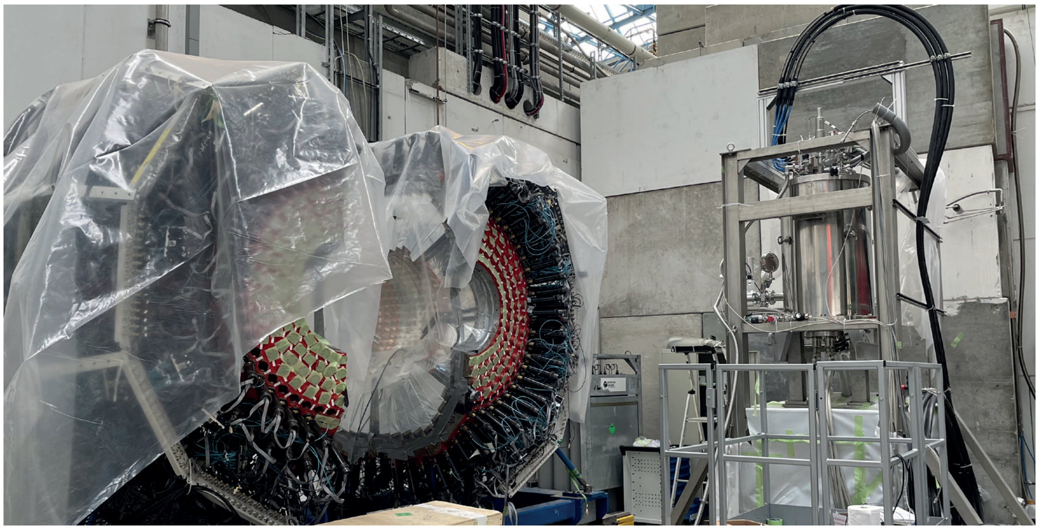


Figure 42. The WASA test stand in the Target Hall of GSI. The central detector is seen on the left, on the right side there is the cooling system with the s.c. solenoid underneath.

The preparation of the WASA@FRS experiment campaign, that is planned for spring 2022, has continued at GSI by the FRS/SFRS department together with the Super-FRS Experiment Collaboration. One of the milestones met in 2020 was the successful reconstruction of the cryogenic system for the superconducting solenoid magnet of the WASA central detector (see Figure 42). A temperature of 4 K has already been reached. The figure shows a photograph of the part of the WASA central detector, the superconducting magnet and its associated cryogenic system. In addition, large arrays of scintillating fiber detectors have been developed and constructed by the collaborators of the High Energy Nuclear Physics Laboratory at RIKEN, and the development of a small fiber detector array is in progress. Upgrading of the Time-of-Flight detector is also on-going at the Meson Science Laboratory of RIKEN. The development of Si vertex detectors is in progress at CSIC-Madrid. With the 2.5 GeV proton beam, which was available in June 2020, a test experiment was performed at the FRS with prototype detectors and a special ion-optical high-acceptance mode to investigate the background suppression capabilities under realistic kinematical and high-luminosity conditions, and indeed the feasibility of the new experimental concept for forward high-resolution spectroscopy with WASA@FRS (i.e.: FRS in combination with decay-particle detection by WASA) has successfully been demonstrated. The preparation of experiments using WASA@FRS will continue and two experiments shall be performed in 2022: S447 for studying light hypernuclei and S490 for studying η'-mesic nuclei.

Outlook to 2021

It is planned to perform the experiments displayed in Figure 36 in 2021. A key activity will be the production, separation and identification of light positron-emitting nuclei (like ^{10,11}C or ^{14,15}O) for first steps towards tumour therapy using radioactive beams and improved PET imaging and related studies on the relevant atomic and nuclear effects in tissue resp. tissue-equivalent materials. On the development side, the department will concentrate on the implementation of WASA@FRS, tests of EXPERT detector components, and the construction of the Cryogenic Stopping Cell CSC for the Super-FRS at FAIR will be started.

Selected publications 2020

- [1] Bagchi, S. ; Kanungo, R. ; Tanaka, Y. K. ; et al: Two-Neutron Halo is Unveiled in ^{29}F. Physical review letters 124(22), 222504 (2020), DOI:10.1103/PhysRevLett.124.222504
- [2] Ayet San Andres, S. ; Mollaebrahimi, A. ; Dickel, T. ; et al: Mass and half-life measurements of neutron-deficient iodine isotopes. The European physical journal / A 56(5), 143 (2020), DOI:10.1140/epja/s10050-020-00153-5
- [3] Bogdanov, O. V. ; Pivovarov, Y. L. ; Tukhfatullin, T. A. ; et al: Isotopic effect in half-wavelength-crystal channeling of relativistic ions.Physics letters / B 802, 135265 (2020), DOI:10.1016/j.physletb.2020.135265
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4.2 Department Nuclear Reactions

Head: Prof. Dr. Thomas Aumann, Technische Universität Darmstadt & GSI
Author: Thomas Aumann

The department Nuclear Reactions develops and operates the R3B (Reactions with Relativistic Radioactive Beams) experiment, which allows for kinematically complete measurements of reactions with heavy-ion beams with typical energies of 0.5 to 1 GeV/nucleon. The scientific aim is to determine and understand the properties of neutron-proton asymmetric nuclei, the properties of astrophysical objects like neutron stars, as well as nucleosynthesis processes in stars, star explosions, and neutron-star mergers by measurements of reactions with short-lived nuclei. A start version of the FAIR R3B experiment has been installed in Cave C at GSI while completion of the detector construction is still ongoing. For the FAIR Phase-0 production beamtime in 2020, the setup has been further completed by adding newly constructed parts. In particular, the CALIFA detector surrounding the target has been further upgraded, and a Si vertex tracker has been added for quasi-free (*p*,2*p*) reactions.

Highlights in 2020

R^{3}B NeuLAND prototype at RIKEN RIBF: Shell structure around ^{28}O

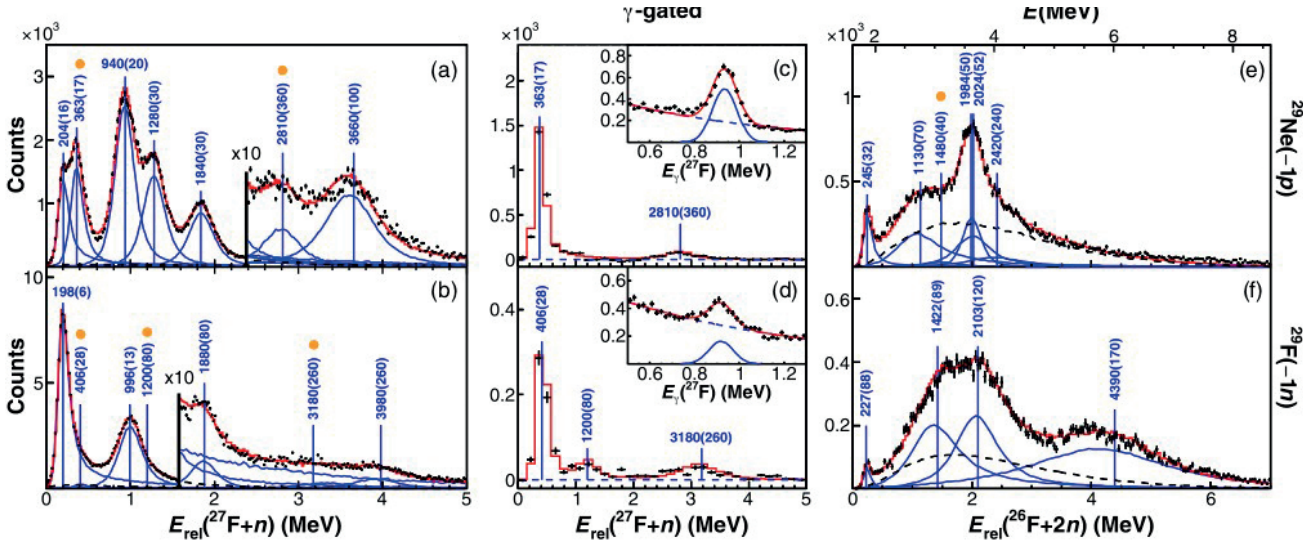

Figure 43. Energy spectra for one- and two-neutron decays of ^{28}F states. Revel, A. et al, Physical review letters 124(15), 152502 (2020), DOI:10.1103/PhysRevLett.124.152502. Copyright (2020) by the American Physical Society.

The R3B collaboration started to collect the harvest from the R3B-NeuLAND campaign at the Radioactive Ion-Beam Factory RIBF at RIKEN with a first publication in Physical Review Letters in May 2020 (PRL 124, 152502 (2020)) on the spectroscopy of unbound states of ^{28}F. Four double-planes of the R^{3}B-NeuLAND detector were installed at the SAMURAI setup at RIBF during the years 2015-2017. The detector could demonstrate its superior performance compared to existing neutron detectors. The addition of NeuLAND to the RIKEN system made it possible, for the first time, to reach extremely neutron-rich nuclei up to four neutrons beyond the neutron drip line, including the long-awaited observation of the four-neutron emitter oxygen ^{28}O with ten more neutrons then the heaviest stable oxygen isotope. The structure evolution of nuclei around ^{28}O provides a benchmark for modern ab initio nuclear theory. One of the experimental campaigns of NeuLAND concentrated on this region. The first result for the structure of ^{28}F (one proton more than oxygen) is presented in Figure 43, showing the energy spectra for the one- and two-neutron decays of unbound ^{28}F states.

Many new states could be resolved and identified, demonstrating the power of the R3B neutron detector due to its superior resolution. The rich spectrum of ^{28}F (Figure 43) directly reflects the drastic change of nuclear structure for these neutron-rich nuclei, as compared to shell-model predictions, and clearly evidences the presence of intruder states from the above-lying *pf* shell, *i.e.*, the non-existence of the N=20 magic number. This result, together with (not-yet published) results on ^{29}F, ^{30}F, and on the ground state of ^{28}O, will provide the basis for answering the long-standing question if ^{28}O is a doubly-magic nucleus, as predicted for decades by mean-field theories, or not. Already the spectra shown in Figure 43 for ^{28}F only, provide indication that this is not the case.

R3B FAIR Phase-0 program

R^{3}B scheduled two experiments in the FAIR Phase-0 beam time in spring 2020. The first was devoted to the investigation of the single-particle structure of neutron-rich Ca isotopes by utilizing quasi-free (p,2p) and (p,pn) proton and neutron-knockout reactions. The experiment thus is capable to study and establish the evolution of the proton Z=20 as well as the neutron N=28, 30 shells including the identification of the most important single-particle configurations in the ground state of these neutron-rich isotopes. The online spectra already demonstrate the expected performance of the newly installed R^{3}B FAIR detection systems. The second experiment, devoted to kinematically complete studies of the fission process, was postponed due to the pandemic situation and re-scheduled for the 2021 program (see below).

Outlook for 2021

Three types of experiments are foreseen to be carried out during the R3B FAIR Phase-0 program in 2021. The R3B detection systems have been further upgraded for this beam-time period. This includes the installation of new CALIFA crystals in the forward direction for detection of high-energy protons and photons, new Fibre tracking detectors for better fragment identification and further improvement of the invariant-mass resolution, as well as the extension of NeuLAND by four double planes to increase the multi-neutron tracking capabilities.

The fission experiment will provide for the first time an event-by-event determination of the projectile excitation prior to fission, in conjunction with full fission-fragment identification and neutron detection. This will provide new insight into the dynamics of the fission process, but also will allow for the first time to extract fission barriers for exotic nuclei. This will open a program to study the evolution of fission barriers in neutron-rich nuclei, which are an important ingredient for understanding the fission recycling in the rapid neutron-capture nucleosynthesis process.

The mass of a neutron star can more precisely determined by astronomical observations. The size of neutron stars for a given mass depends on the neutron pressure of neutron-rich matter at different densities. The density dependence of the pressure for asymmetric nuclear matter around saturation density is described by the slope of the symmetry energy. The same neutron pressure is responsible for the development of neutron skins in the ground state of heavy neutron-rich nuclei, which is poorly constrained by experimental data. R3B will apply a newly developed method to determine this quantity accurately by a measurement of total neutron-removal cross sections. The scheduled experiment in 2021 will measure these cross sections along the Sn isotopic chain up to ^{132}Sn.

The ^{12}C(α,γ)^{16}O reaction is one of the most important reactions in nuclear astrophysics, which determines the ^{12}C/^{16}O ratio in massive stars after the He-burning stage, and thus largely influences the further evolution of stars and the associated element synthesis and resulting abundancies. R3B will measure the inverse ^{16}O(α,γ)^{12}C reaction by electromagnetic excitation at relativistic beam energies. The new R^{3}B setup allows to reconstruct the relative energy of the fragments in the final state with high resolution and efficiency, and to cover thereby a wide energy window. The goal is to determine the cross section and thus the astrophysical S-factor down to a centre-of-mass energy of 800 keV, which none of the many previous experimental attempts has accomplished.

Selected publications of 2020

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4.3 Department Nuclear Spectroscopy

Head: Dr. Jürgen Gerl, GSI
Authors: J. Gerl, M. Górska, H. Albers

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 2020

Nuclear structure experiments

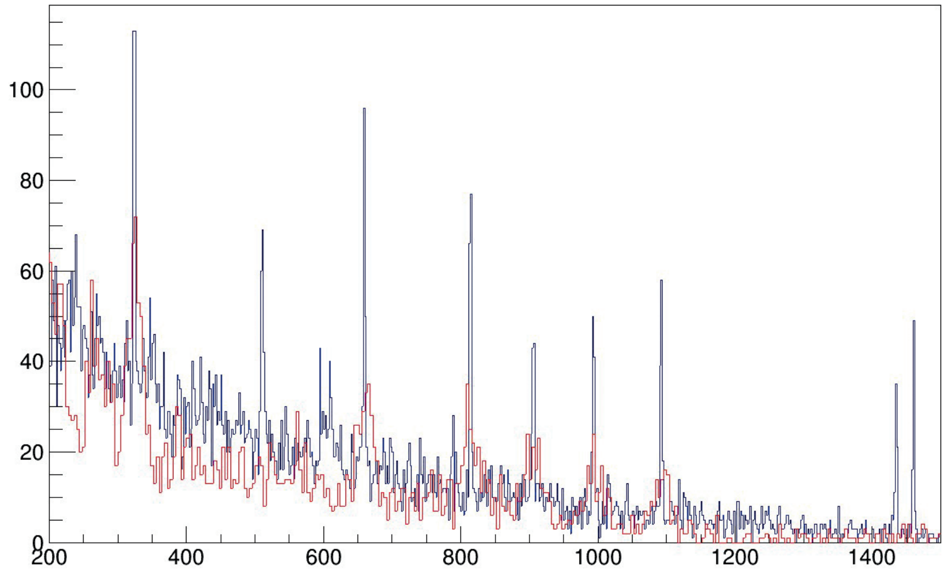

Figure 44. Preliminary gamma spectra of ^{94}Pd isomeric decays detected by GALILEO (blue) and FATIMA (red). The energy scale is in keV.

Activities concentrated on the optimization, in-beam commissioning and performance of the first DESPEC experiments within the NUSTAR FAIR Phase-0 campaign. The early implementation of the so-called Fast Timing Setup [1] is 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. An extended commissioning phase at the FRS helped to assure proper functioning of this very complex detection system, while the Corona pandemic limited the physics opportunities to only one experiment: S480. It dealt with the structure of the heaviest N=Z nuclei, with seniority and electromagnetic transition rates in ^{94}Pd in particular. ^{94}Pd ions were formed in the fragmentation of a ^{124}Xe beam, identified by the FRS and stopped in AIDA. Subsequent isomeric decays were detected in the gamma detectors of the setup. FATIMA allows the precision measurement of lifetimes of excited states in ^{94}Pd$_{48}$. This nucleus is of particular interest as it lies on the boundary between the N=Z=46 system ^{92}Pd, where proton-neutron pairing effects are of main importance, and the N=50 closed shell system ^{96}Pd$_{50}$, with proton residual interactions and a typical seniority scheme of first excited states. The analysis of the data is ongoing.

Detectors and infrastructure

In 2020 the work on DEGAS has continued with the installation and test of the first electrically cooled DEGAS triple detector. The remaining noise of the first prototype e-cooler proved insignificant, its cooling power agreed with specifications, and the energy resolution of the detector was as expected, with measured values ranging from 2.6 keV to 3.0 keV for ^{60}Co energies.

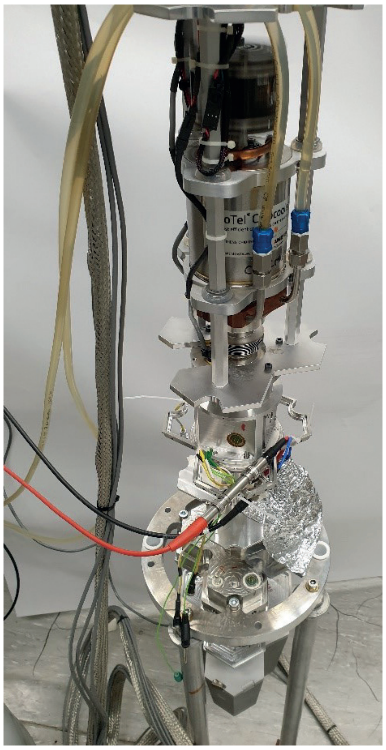

Figure 45. Prototype of the electrically cooled DEGAS triple Ge detector.

The current implantation scheme consists of double or triple layers of AIDA Double Sided Silicon Strip Detectors DSSSD planked by bPlast plastic detectors on the upstream and downstream side with respect to the beam. This enables beta particles escaping from AIDA to be detected by bPlast [2], and thus fast time coincidences with FATIMA. However, for geometrical reasons the efficiency of this set-up is limited to <30%. To overcome this limitation, the development of a Fiber Implanter – FIMP complementing AIDA for fast timing experiments has started. It will consist of a dense packed array of crossing organic scintillation fibers, read out individually by SiPMs. A demonstrator setup with 16+16 fibers has been investigated at the GSI scanner and in-beam. Time resolution of <400 ps (FWHM) has been obtained. Heavy ion punch-through, implantation and beta decay events are distinguishable, employing GSI TAMEX electronics. The analysis of the efficiency for the detection of betas is on-going.

The advent of the coronavirus pandemic has propelled a global shift towards remote and distance working. In response to this, new and innovative ways of establishing monitoring and control of detector hardware, data acquisition and data management/analysis from outside of the GSI campus have been developed successfully. This included hardware, software and procedural changes required to run experiments at GSI from off site in order to limit the number of people on campus to a core minimum. The ability to remotely access and control experimental features significantly benefits all kinds of nuclear physics experiments via:

a) minimization of on-site operations (reducing 'downtime' due to opening of experimental areas to access equipment, minimizing requirement of on-call experts to come in person to the facilities)
b) early problem recognition and intervention
c) fast and effective information and expertise exchange between collaborators
d) training and development of early-career researchers

Applications

A new initiative has been started: The ECSIDE - European Consortium for Smart and Innovative Detector Ensemble – project, which aims to develop a novel type of gamma-detection system, bringing unprecedented sensitivity. ECSIDE will realize smart detector systems based on compact arrays of mini detectors, manufactured using highly advanced and sophisticated 3-D printing technology. Machine learning (ML) and Artificial Intelligence (AI) concepts will be employed for the first time with 4D gamma tracking and autonomous evaluation and interpretation of detected radiation. This radically new detector concept will expand the possibilities of gamma-radiation detection systems tremendously. It will enable

- location of radioactive fallout clouds in real time for environmental monitoring,
- important spectroscopic information at high dose rates prevalent in nuclear accidents
- early-warning schemes for earthquakes based on sensitive precursor measurement,
- climate change investigations employing specific radiotracers,
- low-cost high-performance medical PET imaging for developing countries,
- novel studies in basic science to uncover the origin of matter in the universe,

and many more, yet unforeseen industrial applications.

Outlook for 2021

In 2021 the department will concentrate on decay studies employing the DESPEC Fast Timing Setup 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 production of DEGAS detectors will be fostered and the development of the full FIMP detector will be started. In addition, first 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 2020

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4.4 SHE departments and HIM SHE section

Department Heads: Prof. Dr. Michael Block, Johannes Gutenberg University Mainz & GSI; Prof. Dr. Christoph E. Düllmann, Johannes Gutenberg University Mainz & GSI
Authors: Brankica Andelic, Ernst Artes, Michael Block, Pierre Chauveau, Premaditya Chhetri, Daniel M. Cox, Christoph E. Düllmann, Dominik Dietzel, Francesca Giacoppo, Michael Götz, Stefan Götz, Raphael Haas, Mustapha Laatiaoui, Oliver Kaleja, Jadambaa Khuyagbaatar, Tom Kieck, Stefan Knecht, Carl-Christian Meyer, Steven Nothhelfer, Valeria Pershina, Sebastian Raeder, Maximilian Rapps, Dennis Renisch, Elisabeth Rickert, Dirk Rudolph, Anton Såmark-Roth, Luis G. Sarmiento, Jessica Warbinek, Alexander Yakushev

In 2020, activities at GSI focused on the UNILAC beamtime within the FAIR Phase-0 program, comprising decay spectroscopy of Fl, chemistry studies of Nh, and laser spectroscopy of Fm and Lr. In addition, the analysis of data obtained in prior beamtimes was continued. At HIM, the advancement of technical and methodological developments, for example for applications in laser spectroscopy and mass spectrometry as well as radionuclide layer production for various applications was most central. In addition, preparations for the beamtime 2021 have been performed.

Synthesis

The search for new elements beyond Og (Z=118) is currently a hot topic in superheavy element research. Attempts to produce the elements 119 and 120 in the ^{50}Ti+^{249}Bk and ^{50}Ti+^{249}Cf reactions were carried out in 2011/2012 at the gas-filled recoil separator TASCA. These reached low cross-cross sensitivities, however, did not result in the discovery of new elements, likely due to aspects of the nuclear reaction mechanism [J. Khuyagbaatar et al., Phys. Rev. C 102, 064602 (2020)]. The reached sensitivity levels are very valuable to enhance the understanding of the nuclear reaction mechanism occurring in beyond-^{48}Ca induced heavy-ion reactions on actinide targets, which have never resulted in the production of SHE to date. While the search for new elements is not currently pursued at GSI, studies of the nuclear reaction mechanism continue, in collaboration with Australian National University in Canberra, Australia. We investigated various deep-inelastic reaction channels in four different reactions potentially suitable for the discovery of element 120 [H.M. Albers et al., Phys. Lett. B 808, 135626 (2020)]. The measured deep-inelastic channels show quasi-fission to be the dominant reaction outcome, however, at different contact timescales. The longest interaction time was found for the ^{50}Ti-induced reaction, i.e., ^{50}Ti+^{249}Cf, which suggests this reaction to be the most promising one in the entrance channel. Therefore, this result confirms that the attempt to synthesize elements 119 and 120 at TASCA in ^{50}Ti-induced reactions was the proper choice [J. Khuyagbaatar et al., Phys. Rev. C 102, 064602 (2020)].

Nuclear structure

Nuclear fission is one of the main issues determining the stability of superheavy nuclei. In the SHE chemistry department the fission process is intensively studied both theoretically [J. Khuyagbaatar, Nucl. Phys. A 1002, 12195 (2020)] as well as experimentally [J. Khuyagbaatar et al., Phys. Rev. Lett. 125, 142504 (2020)]. In a semi-empirical description of all known half-lives of even-even heaviest nuclei [J. Khuyagbaatar, Nucl. Phys. A 1002, 12195 (2020).], it has been shown that fission might be one of the main decay modes for the yet unknown element 120. Accordingly, this decay mode should also be considered in any discovery experiment on element 120. The obtained results also support that a lowering of the outer fission barrier occurs in the superheavy nuclei, which had been inferred previously from the analysis of the electron capture delayed fission. Thus, the new results support the predicted large Electron-Capture Delayed Fission (ECDF) branching in superheavy elements. The ECDF phenomenon is a promising topic for examining the fission properties of superheavy nuclei. The occurrence of this decay mode has been examined in the new isotope ^{244}Md at TASCA [J. Khuyagbaatar et al., Phys. Rev. Lett. 125, 142504 (2020)]. No ECDF branch was discovered because the new isotope ^{244}Md decays mostly by α-particle emission. At the same time, we have observed a short-lived fission activity, which could not unambiguously be attributed to a specific physical process and deserves further investigation. The work on ^{244}Md was included in the list of the few most important achievements in the fields of particle-, nuclear and accelerator physics [L. Kleinen, Europa bleibt Herrin der Ringe und Quantenoptik erhellt fortan die starke Kraft, Jahresrückblick Teilchen-, Kern- und Beschleunigerphysik 2020, pro-physik.de, 28.12.2020].

In the wake of the discovery of superheavy elements, nuclear spectroscopy experiments aim at providing anchor points at the uppermost end of the nuclear chart for nuclear structure theory, which otherwise had to solely rely on extrapolations. In two runs in 2019 and 2020, such a nuclear spectroscopy experiment was conducted to study α-decay chains stemming from isotopes of flerovium (element $Z = 114$). One incentive to study flerovium isotopes is that many, but not all, nuclear structure models or model parametrizations favour $Z = 114$ as the next magic proton number beyond lead, $Z = 82$. This was studied in an experiment, in which an upgraded TASISpec decay station was placed behind the gas-filled separator TASCA. The fusion-evaporation reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu provided a total of 32 flerovium-candidate decay chains in effectively 18 days of beam time. Two and eleven decay chains were firmly assigned to even-even ^{286}Fl and ^{288}Fl isotopes, respectively. The – admittedly unexpected – observations include (i) an excited 0^+ state at 0.62(4) MeV excitation energy in ^{282}Cn, and (ii) a $Q_\alpha = 9.46(1)$ MeV decay branch, $b_\alpha \approx 2\%$, from ^{284}Cn into ^{280}Ds [A. Såmark-Roth et al., Phys. Rev. Lett. 126, 032503 (2021)]. Both observations indicate that there is hardly any shell gap at proton number $Z = 114$ - at least not at neutron numbers $N \approx 172$-174. This statement is supported by demanding beyond-mean-field model calculations, which include the necessary triaxial shapes [J.L. Egido and A. Jungclaus, Phys. Rev. Lett. 125, 192504 (2020)]. The existence of the excited 0^+ state in ^{282}Cn requires an understanding of both shape coexistence and shape transitions for the heaviest elements. Second, using the known $Q_\alpha = 10.79(4)$ MeV for the ^{292}Lv -> ^{288}Fl α decay as well as the now precisely measured $Q_\alpha = 10.06(1)$ MeV for ^{288}Fl -> ^{284}Ds, a smooth Q_α sequence across $Z = 114$ could be established. Hardly any kink is observed at $Z = 114$, while it is characteristic for any pronounced shell gap. The present results thus reinforce the benchmarking capability of nuclear spectroscopy experiments in the superheavy element regime. Future technical developments on beam intensity, target integrity, and detection efficiency should allow to "wring out tantalizing physics from compound nucleus production data where cross-sections are in the picobarn range" (quote referee report of [A. Såmark-Roth et al., Phys. Rev. Lett. 126,032503 (2021)]).

Nuclear isomers provide valuable information about excited states in nuclei and the interaction or coupling of nucleons staying in different nuclear levels. Of specific interest in well-deformed nuclei are *K*-isomers, arising from breaking up nucleon pairs and exciting them into different nuclear states. In a recent experiment we investigated possible population of *K* isomers in ^{255}Rf produced in the reaction ^{207}Pb(^{50}Ti,2n)^{255}Rf. To detect events from the decay of such isomeric states, correlations of the type Evaporation Residue ER (implantation signal) - CE (conversion electron, possibly in prompt coincidence with a γ event) - α decay / Spontaneous Fission SF (from ^{255}Rf or ^{251}No) were analysed. As one has to consider a possible population of the known $5/2^-$ isomeric state in ^{255}Rf ($E^* \approx 135$ keV, $T_{1/2} = 50 \pm 17 \mu$s [S. Antalic, F.P. Heßberger, D. Ackermann, S. Heinz, S. Hofmann, B. Kindler, J. Khuyagbaatar, B. Lommel, R. Mann, Eur. Phys. J. A51, 41 (2015)], which essentially decays by CE emission of $E < 150$ keV, the energy range of CE from decay of possible *K* isomers was restricted to $E > 200$ keV. Two activities were identified [P. Mosat, F.P. Heßberger, S. Antalic, D. Ackermann, B. Andel, M. Block, S. Hofmann, Z. Kalaninova, B. Kindler, M. Laatiaoui, B. Lommel, A.K. Mistry, J. Piot, M. Vostinar, Phys. Rev. C 101, 034310 (2020).]: a) one with a half-life of $T_{1/2} = 38\ {+12}/{-7}\ \mu$s and CE energies essentially below 370 keV, and b) a second one with a half-life of $T_{1/2} = 15{+6}/{-4}\ \mu$s and CE energies essentially above 370 keV. Based on the observation of three correlations of the type ER - CE1 - CE2 - α/SF the events with the longer half-life were attributed to an isomeric state at $E^* \approx (1.15$-$1.45)$ MeV, the one with the shorter half-life to a state at $E^* \approx (0.9$-$1.2)$ MeV. For some of the CE also γ events were observed in prompt coincidence, but no line structure was visible due to low statistics. Also, no spin and parity values could be determined. This has to be left for further, more detailed studies.

Atomic physics

The investigation of the heaviest elements by laser spectroscopy at SHIP has been further extended. In the GSI beamtime 2020, the atomic level search in lawrencium Lr was started using the RADRIS method. It was shown that hafnium Hf is a suitable filament material for the efficient neutralization and evaporation of Lr with low background level from surface ionization. A significant part of the range, in which atomic transitions were predicted by atomic theory, was scanned using a two-step laser excitation scheme, but no evidence for a transition was observed, yet. In addition to the Lr level search, for the first time laser spectroscopy of $^{248-250}$Fm was performed by a variant of the RADRIS method. These fermium Fm isotopes are inaccessible in a direct production scheme and were produced via α decay of $^{252-254}$No. A two-step laser excitation scheme was used with the second step populating an autoionizing state. We measured the isotope shift of the 5,112 cm^{-1} transition in $^{248-250}$Fm. However, the hyperfine splitting of this transition in ^{249}Fm was not fully resolved due to limited statistics. This work extended optical spectroscopy in the Fm isotopes to neutron-deficient isotopes below the N = 152 deformed neutron shell closure complementing recent work at the RISIKO mass separator of Mainz university performed in collaboration with the SHE departments at GSI and HIM. There, the long-lived isotope ^{257}Fm was studied by resonance ionization laser spectroscopy in a hot-cavity ion source offline. The same technique was used to study the einsteinium isotopes $^{253-255}$Es. In 2020, an injection-seeded laser was used to measure the complex hyperfine structure splitting of three different transitions in ^{254}Es with increased spectral resolution. The obtained data will provide information of the nuclear moments and the changes in the mean-square charge radii in the Fm and Es isotopes.

For future on-line measurements on the heaviest elements with improved spectral resolution, a new setup for in-gas jet laser spectroscopy was commissioned. Different de Laval nozzles were compared to identify the optimum pressure conditions to form a gas jet with a Mach number of 8. A spectral resolution of about 400 MHz was obtained measuring resonances in the stable isotope ^{174}Yb, a chemical homologue of No. This paves the way for a measurement of the K=8$^-$ isomer in ^{254}No in the 2022 beamtime at GSI.

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

The first chemical study of Nh at TASCA was attempted in 2016. The non-observation of any Nh events in a three-week experiment pointed at losses of Nh atoms on the way to the detection system COMPACT due to a high chemical reactivity of Nh. Since then, several preparatory studies with chemically reactive metals (Tl, Pb, Fr) have been performed in 2018 and 2019, aiming at a faster and more efficient extraction of short-lived and chemically reactive species into the gas chromatography and detection setup, extended with a new detector array (16-element miniCOMPACT), which was directly attached to the recoil transfer chamber. Based on the obtained positive results an advanced 64-element miniCOMPACT detector was built. During a beamtime of 20 days, the reaction ^{48}Ca + ^{243}Am was used to produce ^{288}Mc in the 3n exit channel. Reaction products were separated in TASCA, thermalized in a newly designed recoil transfer chamber (RTC) and transferred into the new advanced miniCOMPACT. Seven decay chains, assigned to ^{288}Mc and ^{284}Nh, were observed. The obtained data are under evaluation and will allow to define the interaction strength of Nh towards SiO_2. The observation of two decay chains originating from ^{288}Mc ($T_{1/2} \approx 170$ ms) is promising for the chemical study of Mc, which is scheduled at GSI for 2021.

Complementing the experiments with the superheavy elements, off-line studies with Pb and Bi as lighter homologs of Fl and Mc were carried out. The short-lived volatile ^{219}Rn was provided from an ^{227}Ac source, which was flushed with flowing gas. The daughters ^{211}Pb and ^{211}Bi were flushed through the RTC into the miniCOMPACT array. Chromatograms were recorded as a function of various parameters like carrier gas type, gas flow rate and pressure, thus characterizing the novel detector array and aiding to optimize the conditions for experiments with superheavy elements. Pb and Bi showed the expected high reactivity towards the silicon dioxide surface of the miniCOMPACT. Furthermore, experiments with oxygen as a reactive gas were carried out. No measurable differences in the distribution were found, suggesting a similar reactivity of the possibly formed lead/bismuth oxides towards the detector surface as the pure elements.

On the way to even more short-lived elements like Lv, the extraction time to transfer the isotopes from the RTC into COMPACT needs to be reduced, as this is significantly longer than the half-lives of even the most long-lived isotopes of all elements beyond Fl. To overcome this limitation, exploratory experiments to study the performance of a buffer gas cell in combination with a COMPACT array were carried out using short-lived α-decaying Hg, Fr, and At radioisotopes. These were produced in ^{40}Ar- and ^{48}Ca-induced nuclear fusion-evaporation reactions, isolated in the recoil separators MARS at Texas A&M University (USA), and TASCA at GSI and thermalized in a gas-stopping cell. From the latter, the nuclear reaction products were extracted into gas-phase chromatographic systems. The efficiency for transporting chemically reactive Fr radioisotopes into the optimized miniCOMPACT gas-chromatography setup was measured and supports that this technique enables the identification of isotopes of volatile as well as non-volatile elements. These studies guide the path towards chemical investigations of superheavy elements beyond flerovium, which are out of reach with currently used setups. However, the stopping power of the presently used gas cell is insufficient for experiments with superheavy elements. To overcome this problem, the design of the advanced “UniCell” has started.

Chemical theory supporting experimental work

In assistance to the coming experiments on the study of reactivity and volatility of Mc and its homolog Bi, calculations of adsorption properties of Bi and Mc on the surfaces of gold and quartz have been performed with the use of the ADF BAND relativistic periodic code. The results have shown that Mc will adsorb on the hydroxylated quartz surface similarly to Nh with an energy of 58 kJ/mol. Adsorption of Bi is much stronger. Both elements will adsorb very strongly on the gold surface with the energy above 200 kJ/mol. With the aim to support gas-phase experiments on the volatility of element 113, Nh, and its homolog Tl, adsorption energy calculations of TlOH and NhOH on the hydroxylated surface of quartz have been performed with the use of the ADF BAND and Quantum Espresso (QE) pseudopotential methods. The preliminary results (-83 kJ/mol with BAND and -69 kJ/mol with QE for TlOH) show that the interaction has a complex nature and that a rearrangement of the surface OH groups occurs. There could also be a formation of H_2O molecules on the surface, from hydrogen atoms and hydroxy groups “ripped” off the surface. This work is ongoing. Further work focuses on the theoretical investigation with molecular ADF on the formation of small molecules of Mc and Ts in COMPACT-type setups. We found that formation of oxides and their reduction with hydrogen is energetically favorable.

Quantum chemical software developments

Quantum chemical studies with a particular focus on molecular properties and reactivities of chemical systems with SHE necessitates treating scalar-relativistic effects, spin-orbit coupling and electron correlation effects on an equal footing. A central aspect of our software developments is therefore to extend the scope of relativistic quantum chemical approaches to SHE in the context of novel electron correlation methods with a particular focus on multiconfigurational approaches. Recently, we presented an implementation of the matrix-product state (MPS) wave function parametrization of the density matrix renormalization group (DMRG) approach within the relativistic quantum chemistry software package DIRAC [S. Knecht, Nachr. Chem. 67, 57 (2019)] which was applied to study electron correlation effects on the valence electronic shell structure of Og [S. Knecht, Nachr. Chem. 67, 57 (2019)].

The DMRG approach provides a polynomially-scaling, efficient means to obtain near-exact full configuration interaction solutions for (very) large active orbital spaces in a systematic and variational manner. Although the DMRG ansatz in an MPS formulation is capable of efficiently treating the static electron correlation problem, ultimately striving for chemical accuracy in the description of chemical reactions and/or spectroscopic properties for SHE requires to take into account dynamical electron correlation. Moreover, orbital relaxation often plays a crucial role for a correct description of chemical properties in ground- and electronically excited states. Hence, work is ongoing describing how the orbital relaxation problem for a relativistic MPS reference wave function can be efficiently tackled in a fully relativistic framework and to address the dynamical electron correlation issue along the lines of non-relativistic developments.

Measurements of fission products from the nuclear reaction between ^{238}U and laser-induced protons at PHELIX

A collaboration between the research departments Plasma Physics and SHE Chemistry succeeded in detecting nuclear reaction products produced by bombarding thin ^{238}U targets with protons generated by short pulses (500 fs) of the high-intensity PHELIX laser (200 J) [P. Boller et al., Sci. Rep. 10, 17183 (2020).]. This process produced, among others, the volatile fission fragments iodine and xenon, which were transported from the target chamber to an activated carbon filter by means of a fast gas-jet transport as it is often used in the chemical study of superheavy elements.

Actinide target production developments

To date, actinide targets for research into superheavy elements are mainly produced using the Molecular Plating (MP) process. Neither the exact chemistry nor the layer modifications induced by heavy-ion irradiation have been fully elucidated so far. For this purpose, MP-produced lanthanide targets were irradiated at different fluences in TASCA and at the M3 branch of the Material Research beamline. Further irradiations with ultra-low-energy particles were carried out at the Offline Deposit Irradiation (ODIn) setup [R. Haas et al., Nucl. Instrum. Meth. A 957, 163366 (2020)] at HIM. The analysis of the irradiated targets with various methods in house and at external partner institutions is ongoing.

To overcome the limitations of classical molecular plating, which is applicable for the production of thin layers with a thickness of at most about 800 mg/cm^2, a novel, triflate-based electrochemical deposition method for target production is being developed. For this, triflate salts of different lanthanides have been synthesized and were activated in the TRIGA reactor. The lanthanide precursors produced in this way were used for extensive experiments series on the electrodeposition from N, N-dimethylformamide (DMF). Layers with thicknesses up to 2000 mg/cm^2 were obtained and were characterized by autoradiography. Circular Tm layers were produced and irradiated with ^{48}Ca beam at TASCA. Characterization is currently ongoing, in collaboration with the Materials Research departments at GSI and at TU Darmstadt. As a next step, this process will be adapted to produce layers in the shape of the TASCA target segment.

Developments for mass measurements of superheavy nuclides

At SHIPTRAP, the vacuum system was further improved by the installation of non-evaporable getter pumps to enable longer measurement times while minimizing losses due to charge exchange and molecule formation. As a consequence, the rate of ^{257}Rf ions available in the SHIPTRAP measurement trap was increased in the 2020 beamtime by almost an order of magnitude compared to 2018 in a preparatory experiment for high-precision mass measurements of Rf and Db isotopes with SHIPTRAP in 2021. Developments for single-ion mass measurements of rare exotic nuclides utilizing a non-destructive electronic detection scheme with the Fourier-transform ion-cyclotron-resonance method were continued. Such methods can be applied in mass measurements of superheavy nuclides with SHIPTRAP and on other exotic nuclides with MATS at FAIR. A novel version of a resonant tank circuit with a quartz resonator serving as the inductor was employed to detect trapped ions in the TRIGA-TRAP Penning trap at room temperature. A sensitivity of some ten ions was achieved and a proof-of-principle mass measurement on ^{206,207}Pb ions was performed with TRIGA-TRAP [S. Lohse, J. Berrocal, S. Böhland, J. van de Laar, M. Block, S. Chenmarev, Ch. E. Düllmann, Sz. Nagy, J. G. Ramírez, and D. Rodríguez, Rev. Sci. Instrum 91, 093202 (2020)]. Further improvements are under way to further increase the sensitivity.

Selected publications of 2020

- [1] Albers, H. M. ; Khuyagbaatar, J. ; Hinde, D. J. ; et al: Zeptosecond contact times for element Z=120 synthesis. Physics letters B 808, 135626 (2020), DOI:10.1016/j.physletb.2020.135626
- [2] Khuyagbaatar, J. ; Albers, H. M. ; Block, M. ; et al: Search for electron-capture delayed fission in the new isotope ^{244}Md. Physical review letters 125, 142504 (2020), DOI:10.1103/PhysRevLett.125.142504
- [3] Khuyagbaatar, J. ; Yakushev, A. ; Düllmann, Ch. E. ; et al: Search for elements 119 and 120. Physical review C 102, 064602 (2020), DOI:10.1103/PhysRevC.102.064602
- [4] Mosat, P. ; Heßberger, F. ; Antalic, S. ; et al: K isomerism in ^{255}Rf and total kinetic energy measurements for spontaneous fission of ^{255,256,258}Rf. Physical review C 101, 034310 (2020), DOI:10.1103/PhysRevC.101.034310

5. Research of the PANDA Departments

Coordination: Prof. Dr. Klaus Peters, Johann Wolfgang Goethe-Universität 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 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 Barrel DIRC detector 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 the contributions to the GlueX DIRC at Jefferson Lab (Newport News, USA) and data analysis at GlueX and BESIII at IHEP (Beijing, China). In order to accomplish the goals, the department teams up within GSI with the Electronics Lab, Detector Lab and the sections EMP and SPECF of the Helmholtz Institute Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

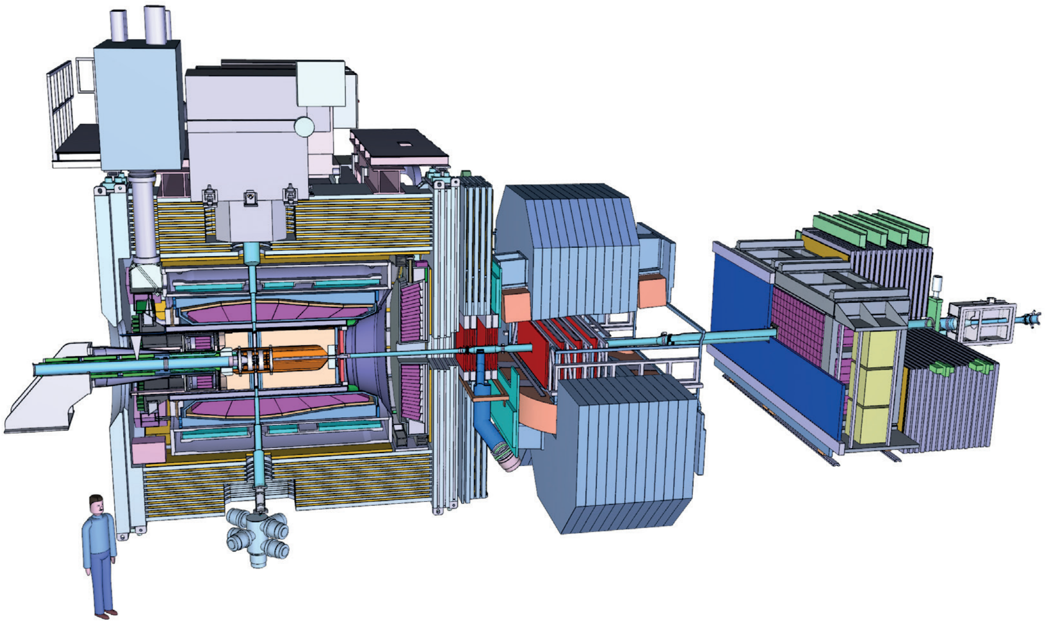


Figure 46. Overview of the PANDA setup at FAIR.

Highlights in 2020

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 (see Figure 46). Core systems of the Day-1 setup are the cluster-jet target, the solenoid magnet with the muon system, the micro vertex detector, the straw tube tracker, 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 are advanced investigations to cover the location of the largest forward tracking stations after the dipole magnet by existing chambers from LHCb. The science case has been detailed and the world-wide competition confirms that the PANDA Day-1 setup as a highly competitive device for fore-front unique research, which has been vetted and scrutinized by the respective FAIR and review committees.

Major achievements of the technical coordination were the two large magnets and the PANDA infrastructure and installation planning. The magnet highlight of the year was the assembly of the yoke of the PANDA at the steel construction company SET in Novosibirsk which is a major milestone for the completion of the PANDA experiment. The detailed design of the HESR-PANDA Dipole Magnet has been completed to start contracting in 2021.

The PANDA Infrastructure and Installation report was finished and submitted to FAIR. It details the support platforms as well as installation and operation processes in the PANDA experimental hall. It is the last key document to finalize the PANDA Construction Memorandum of Understanding, to be signed in 2021.

Simulation and analysis accomplishments were manifold. The two highlights in simulation work for PANDA included machine learning (ML) based selection techniques for the software trigger as well as investigations concerning the X(3872) using PANDA's unique lineshape capabilities. In addition, the first part of the semininclusive data analysis for BES3 has been finalized and the comprehensive η_c search at BES3 in the e+e- -collision energy range 4.18 to 4.60 GeV has been published.

The PANDA Barrel DIRC project reached an important milestone in 2020: The series production of 98 fused silica bars by Nikon Corp., Japan was successfully completed in November 2020, about 5 months ahead of schedule. Based on the high quality of these bars, GSI placed an order for an additional 14 bars as contingency and for assembly tests. The call for tenders for the Barrel DIRC photon sensors concluded in December 2020. Following the detailed characterization of evaluation samples from two vendors, the order for 155 micro-channel plate PMTs (MCP-PMTs) was placed with Photonis Netherlands BV. The delivery of the first MCP-PMTs is expected in July 2021.

5.1 PANDA Technical Coordination

Head: Prof. Dr. Klaus Peters, GSI
Authors: Klaus Peters, Lars Schmitt, Anastasios Belias

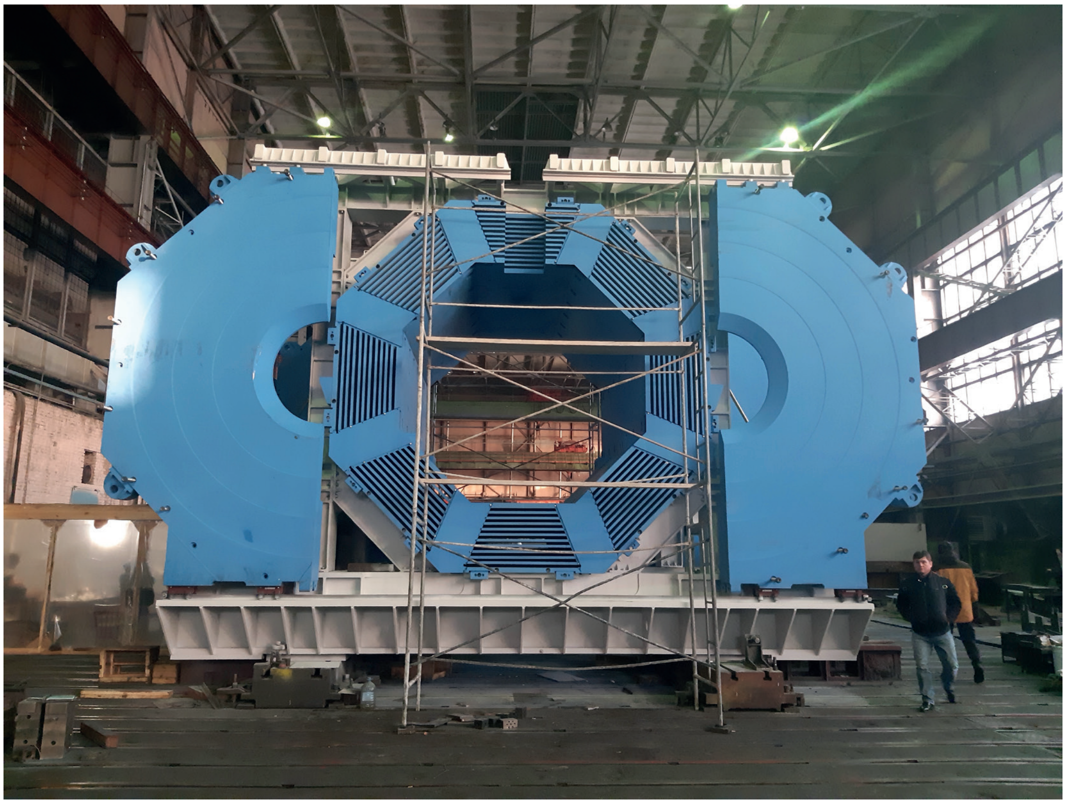


Figure 47. PANDA magnet yoke.

The highlight of the year was the assembly of the 400-ton yoke of the PANDA detector at the steel construction company SET in Novosibirsk (see Figure 47). The final tests of the doors were done end of December 2020.

The assembly of the yoke octants was aided by a star shaped installation tool. After its removal, the octants stayed in place with minimal deviation. All parts were surveyed with a laser tracker employing fixed fiducial marks even during the assembly process, which facilitates the whole operation providing much better precision. No mechanical stoppers were used, as their precision would be too low.

The four doors, two downstream and two upstream, were bolted to the yoke in their closed position. Before opening the doors, the bolts were unfastened and the doors were lowered to the sliding rails, resting them on heavy weight rollers. The 22-ton wing doors can be opened by two persons, using a simple manual winch to move the doors on the rollers.

Further notable progress was the passing of the Conceptual Design Review of the local cryogenics of the solenoid magnet in cooperation with the FAIR cryogenics team and experts from the ATLAS magnet group from CERN. Significant progress was made in the prototyping of the superconducting cable paving the way for the start of production in 2021, for which all required contracts of the Russian joint venture of BINP, VNIIKP, VNIINM and SarKO were signed in 2020.

The BINP team worked out the detailed design of the HESR-PANDA Dipole Magnet in close consultations with the PANDA team at GSI and the HESR team at FZ Jülich up to the level of the specifications for the construction to be contracted in Q1 2021. The optimisation of supports, coil arrangement, field clamps and power converter were discussed throughout the year 2020.

Production drawings, FEM calculations for stability proofs and installation procedures were worked out.

The PANDA Infrastructure and Installation report was submitted to FAIR ECE for review in September 2020. This document presents 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 PANDA coordination team performed a concerted effort to work out the detailed specifications of the PANDA infrastructure regarding support structures and supply infrastructures. The result is the design of an integrated set of versatile platforms serving maximally the needs of the PANDA systems while preserving cost-efficient implementations. Support structures include platforms, support frames, rails and movements systems and installation devices. Supply infrastructure includes drag chains, cable trays, electrical power distribution and grounding, cooling water and technical gases. The implementation of integration requirements and interfaces to all PANDA systems was done in extended communication and close consultation with the detector and magnet groups. All boundary conditions on alignment procedures and certification were taken into consideration.

5.2 Hadron Physics Software, Trigger, and Analysis

Head: Prof. Dr. Klaus Peters, GSI
Authors: Klaus Peters, Klaus Götzen

For the PANDA online event selection (software trigger) various methods in the field of machine learning (ML) have been investigated. In that respect an optimisation concerning dimension reduction and ranking of input features has been carried out with the result, that 70% of the input variables contribute about 95% of information. In total seven different kinds of network architectures have been tested. Finally a residual convolutional neural network in binary classification mode has been selected, which showed a relative efficiency gain of up to +140% compared to the conventional threshold based classification scheme that was redone and analysed in parallel on the same simulated Monte Carlo data sets.

Triggered by a publication by LHCb concerning the measurement of the lineshape of the $\chi_{c1}(3872)$ a PANDA simulation study was carried out about the same subject. While LHCb, despite its precise measurements of resonance parameters, is not able to distinguish different theoretical models, it was shown, that PANDA is able to distinguish between the two models under investigation (Breit-Wigner and Flatté-like lineshape) with probabilities of more than about 90 - 98% across the full parameter range studied, depending on the mode HESR is operated.

Concerning the analysis activities of the BESIII data, the focus lies on the search for yet unknown decay channels of the puzzling and presumably exotic ψ(4230)/ψ(4330) resonances formerly named Y(4260). The production of the ground state charmonium η_c in e^+e^- collisions recoiling against $\pi^+\pi^-\pi^0$ was observed, and the measured energy dependent cross section suggests the intermediate production of the ψ(4230). A possible exotic Z_c was not seen in the subsequent decay. The analysis was accepted by Physics Review D and is meanwhile (2021) published.

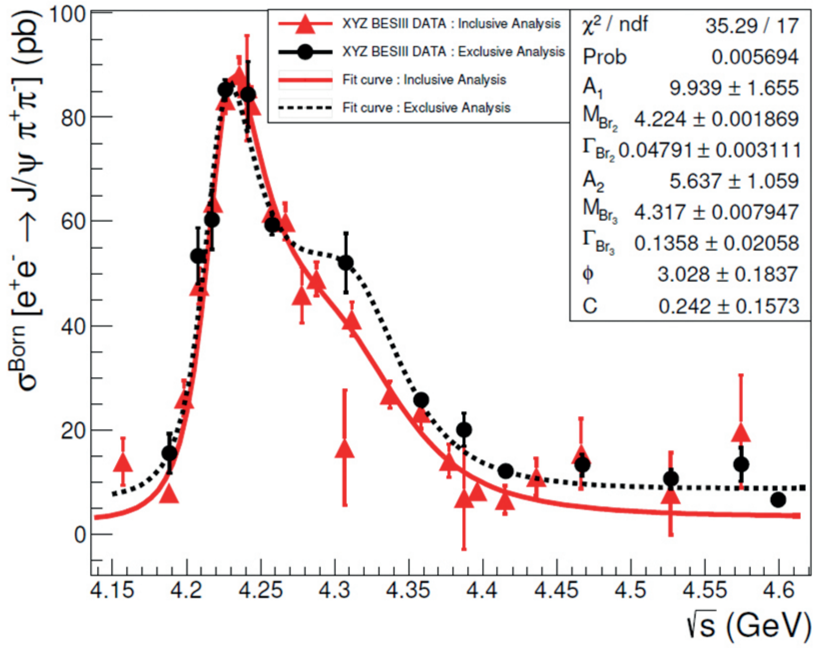


Figure 48. Energy dependent cross sections of $e^+e^- \to J/\psi_{cc}\pi^+\pi^-$ for the xyz BESIII data. Previuos inclusive measurements are shown in black (BESIII, Phys. Rev Lett. 118 (2017), 092001). New exclusive measurements are shown in red (taken from thesis S. Nakhoul, Frankfurt/M, 2020).

The inclusive analysis of $e^+e^- \to X_{cc}\pi^+\pi^-$ was finalised in the course of a PhD thesis. As a result the energy dependent cross sections of the production of $J/\psi\pi^+\pi^-$ and $h_c\pi^+\pi^-$ were investigated, resulting in improved measurements of the Breit-Wigner parameters m_0 and Γ of the ψ(4230) and ψ(4330). The also measured cross section of e^+e^- → anti-D^0 confirmed previous measurements but does not show a contribution from an intermediate ψ(4230) or ψ(4330) resonance (see Figure 48).

The search for possible hyperon production in the decays of the two resonances is carried out by performing an energy dependent inclusive cross section measurement of reactions $e^+e^- \rightarrow \Lambda X$ and $e^+e^- \rightarrow \Sigma X$ with X being arbitrary recoil systems. While first preliminary results are already available, the analysis is still ongoing.

The analysis of the GlueX data searching for the strangeonium-like exotic candidate φ(2170) decaying to $\varphi\pi^+\pi^-$ with and without an intermediate decay $f_0(980) \rightarrow \pi^+\pi^-$ has been completed in the course of a PhD thesis. While a precise cross section measurement of the processes $\gamma p \rightarrow \varphi\pi^+\pi^- p$ (beam energy and momentum transfer dependent) and $\gamma p \rightarrow \varphi f_0(980) p$ was carried out for the four large data sets taking in 2016 – 2018, the production of the exotic candidate itself was determined as an upper limit measurement on the cross section.

5.3 PANDA detector developments

Head: Dr. Joachim Schwiening, GSI
Author: Joachim 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 EIC detector (at BNL, USA).

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 2020 on the construction of the most expensive and longest lead-time PANDA Barrel DIRC components.

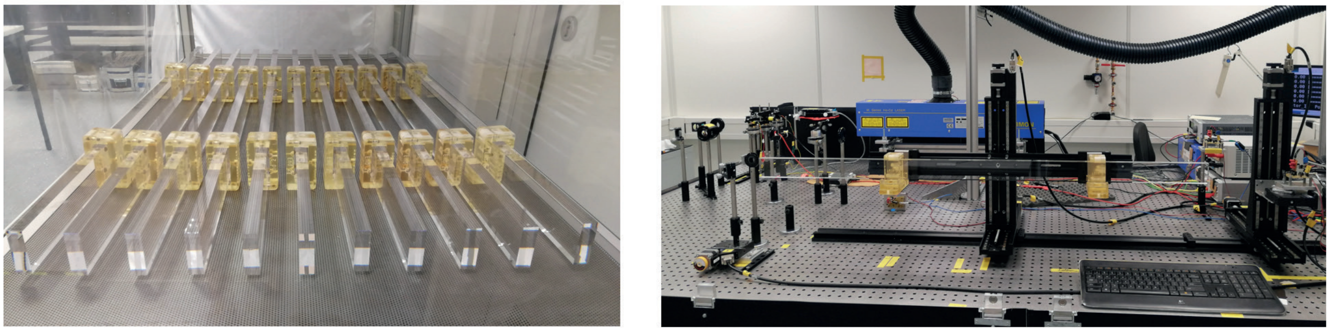


Figure 49. Lef: silica bars prepared for testing, right: laser testing setup.

The contract for the series production of 98 fused silica bars was awarded to Nikon Corp., Japan, in September 2019. The first bars were delivered to GSI in March 2020. The bars were inspected, put into custom 3D-printed holders, and placed under a HEPA filter on a clean bench (see Figure 46). Detailed measurements of the optical and mechanical properties, performed at Nikon and at GSI, demonstrated that the bars meet all production specifications. Frequent production meetings between experts at Nikon and GSI ensured that the series production proceeded quickly, leading to the delivery of the final bars in November 2020, about 5 months ahead of the original schedule. Following the initial quality assurance measurements, GSI placed an order for 14 additional bars as contingency. These bars will be used for tests of the gluing procedure in the DIRC laboratory at HI Mainz and in the construction of a spare bar box. Meanwhile, detailed measurements of the quality of the internal surface of the DIRC bars are ongoing at GSI. A system of six lasers (see Figure 49) is used to measure the coefficient of total internal reflection as a function of the laser wavelength, providing insight into possible subsurface damage effects created during the polishing process.

The call for tenders for the Barrel DIRC photon sensors, the micro-channel plate PMTs (MCP-PMTs), was another 2020 activity focus of the DIRC groups at GSI and Erlangen University. The two leading vendors were asked to produce two samples each to validate their ability to meet the rather challenging specifications. These MCP-PMTs were delivered to GSI in the spring of 2020 and evaluated by the Erlangen group in the sensor laboratory at Erlangen University and in the 2 Tesla dipole magnet at FZ Jülich. Based on these results the contract for 155 MCP-PMTs was awarded to Photonis Netherlands BV in December 2020. The delivery of the first-of-series units is expected in July 2021.

In the spring of 2020, the GlueX experiment at Jefferson Lab performed the first physics run with the new DIRC detector upgrade. The DIRC system was commissioned in 2019 and significantly improves the particle identification (PID) capabilities to extend the physics reach for the high-luminosity GlueX-II run. The PANDA DIRC team from GSI participated in the operation and data analysis of the GlueX DIRC detector. This FAIR Phase-0 activity provides an opportunity to validate the simulation, reconstruction, and particle identification algorithms, developed for the PANDA Barrel DIRC, using real experimental data. The data collected in 2020 show good agreement with the simulation in terms of Cherenkov hit pattern and Cherenkov angle resolution per photon. The remaining differences in the photon yield and pi/K separation power are under investigation and expected to lead to further improvement of the alignment and calibration procedure, as well as the simulation code, providing valuable experience for the PANDA Barrel DIRC.

Selected publications of 2020

- [1] Adhikari, S. ; Akondi, C. S. ; Al Ghoul, H. ; et al: The GlueX beamline and detector. Nuclear instruments & methods in physics research / A 987, 164807 (2021), DOI:10.1016/j.nima.2020.164807
- [2] Schwarz, C. ; Ali, A. ; Belias, A. ; et al: Status of the PANDA Barrel DIRC. International Conference on Instrumentation for Colliding Beam Physics, INSTR20, Novosibirsk, Russian Federation, 24 Feb 2020 - 28 Feb 2020 Journal of Instrumentation 15(03), C03055 (2020), DOI:10.1088/1748-0221/15/03/C03055

6. Research of the Theory department

Heads: Prof. Dr. Gabriel Martínez, Technische Universität Darmstadt & GSI
Authors: Andreas Bauswein, Hannah Elfner (GU Frankfurt & GSI), Matthias F. M. Lutz (TU Darmstadt University), Gabriel Martínez-Pinedo (TU Darmstadt and GSI)

Highlights in 2020

The group ‚Transport and Experiment Simulations‘ focuses on the development of dynamical non-equilibrium approaches for the description of heavy-ion collisions. The main goal is the exploration of the QCD phase diagram and the study of the nature of the transition from the quark-gluon plasma to hadrons in particular at finite baryon density.

The UrQMD approach has been employed to assess chemical freezeout conditions in heavy-ion reactions over a large energy range. With a combination of coarse-grained transport calculation and tracing back the interactions of individual particles the criterion of constant energy per particle of ~ 1 GeV could be confirmed. The actual chemical freezeout is determined by an interplay of individual inelastic cross-sections with the expansion rate of the system [Eur. Phys. J. A 56(10) (2020) 267].

In a collaboration between scientists from the US, France and GSI, the influence of non-equilibrium, initial conditions, bulk dynamics and elementary collisions on charm observables have been investigated. This is relevant for measurements of the ALICE collaboration at LHC. Two different theoretical approaches, the PHSD model as a microscopic transport approach as well as the linearised Boltzmann approach, have been employed to study differences due to the elementary interactions of the heavy quarks with the surrounding medium. Due to the complex interplay of several ingredients concerning the bulk evolution of the system and the treatment of charm quark interactions, different theoretical calculations match the same set of experimental data well. Therefore, this work indicates the importance of non-equilibrium effects and the systematic limitations of extracting knowledge about QCD matter from basic observables. Ways on how to remedy those limitations are outlined [Phys. Rev. C 101 (2020) 044903].

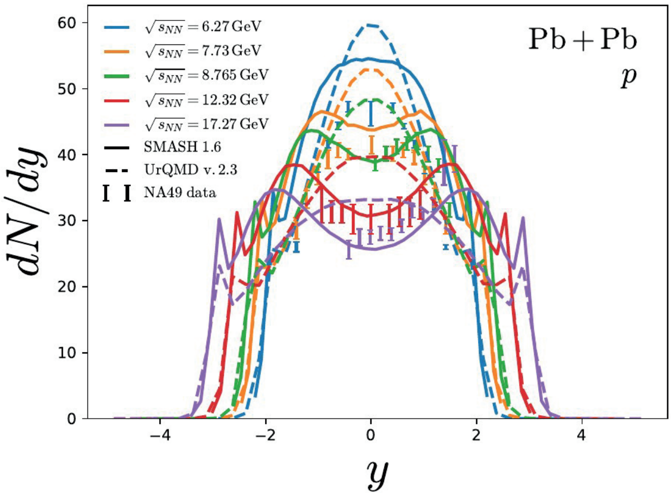


Figure 50. Rapidity distribution of protons at different beam energies. The change from a Gaussian shape to a double-peak structure indicates the difference in the stopping dynamics. Calculations within SMASH and UrQMD are compared to experimental measurements from the NA49 collaboration. Figure: Mohs, J.; Ryu, S. ; Elfner, H.*,Journal of physics G 47(6), 065101 (2020), 10.1088/1361-6471/ab7bd1, ccby3 Mohs et al., J. Phys. G 47 065101 (2020).

The hadronic transport approach SMASH has been extended to higher beam energies above the SIS18 energy range by including particle production via string excitation and fragmentation. For the intermediate range the string excitation has been adopted from the UrQMD approach while fragmentation and hard scatterings are handled via the well established PYTHIA8 framework. After tuning the results to experimental data from elementary proton-proton collisions, the approach has been employed to study the rapidity distribution of protons and net protons in heavy-ion collisions over a large beam energy range. The qualitative change from a Gaussian shape to a double-peak structure can be nicely reproduced. This in important ingredient to understand the stopping dynamics in heavy-ion collisions that are very important in the context of CBM at FAIR [J. Phys. G 47(6) (2020) 065101].

The group "Nuclear Structure and Nuclear Astrophysics" combines 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.

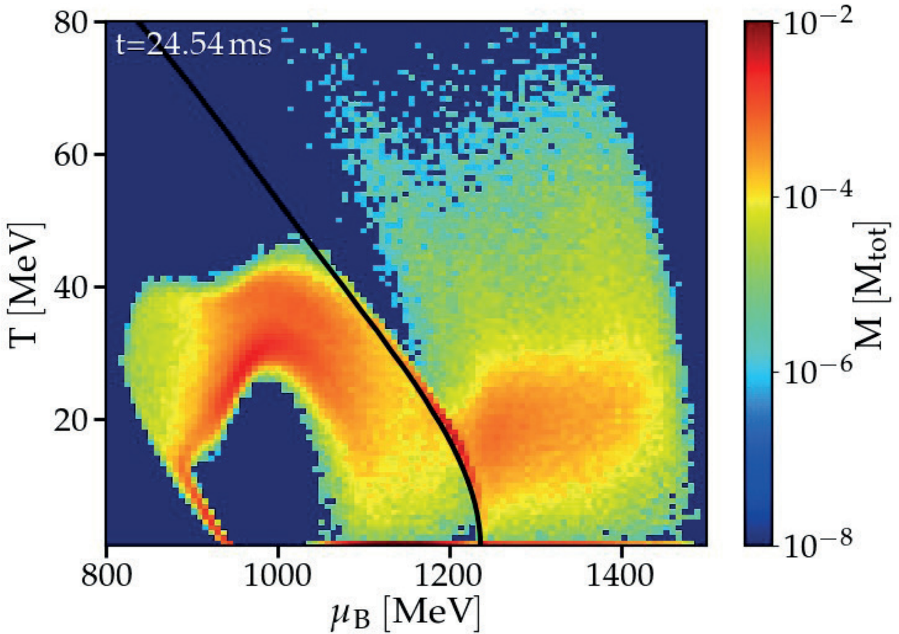


Figure 51. Distribution of matter during a neutron star merger in the phase diagram of matter. Black curve depicts the phase transition to deconfined quark matter. In the shown postmerger stage a substantial amount of matter is present as deconfined quarks. Typical temperatures reach several 10 MeV. Figure taken from: Blacker, S. ; Bastian, N. F. ; Bauswein, A. et al, Physical Review D 102(12), 123023 (2020), DOI:10.1103/PhysRevD.102.123023. Copyright (2020) by the American Physical Society.

One of the most basic characteristics of a neutron star merger is the immediate outcome of the coalescence, i.e. the question whether or not a black hole forms after the collision. The collapse behavior has direct implications for the different observables of a merger like in particular the postmerger gravitational-wave emission, the r-process nucleosynthesis and the electro-magnetic counterpart throughout all wavebands from radio to gamma radiation. Analyzing more than 300 relativistic hydrodynamical HPC simulations of the merger process, a new survey provides a detailed understanding of the dependencies of the collapse behavior on the properties of the high-density equation of state [Bauswein, A., Blacker, S., Vijayan, V.; et al. Equation of state constraints from the threshold binary mass for prompt collapse of neutron star mergers. Physical review letters 125, 141103 (2020) DOI:10.1103/PhysRevLett.125.141103]. These dependencies in turn offer the possibility to gain new insights into the very high-density regime of matter from observations which inform about the merger outcome. Since black hole formation has such a significant impact on observables, different types of measurements can be employed for constraints on the high-density equation of state. In particular, the new study has pointed out that the hadron-quark phase transition leaves a characteristic imprint on the collapse behavior. See cover of this GSI-FAIR Scientific Report.

In another extensive study of postmerger gravitational-wave signals members of the theory department have worked out a procedure to constrain the onset density of the hadron-quark phase transition from observations of neutron star mergers [Blacker, S., Bastian, N.-U., Bauswein, A., et al; Constraining the onset density of the hadron-quark phase transition with gravitational-wave observations [Physical Review D 102, 123023 (2020) DOI:10.1103/PhysRevD.102.123023].

If such future measurements provide evidence for the occurrence of deconfined quarks in neutron stars, the gravitational wave signal will provide an upper bound on the onset density of the phase transition. On the other hand, observations which do not show a signature of a quark phase in compact stars, yield a lower limit on the density of the QCD phase transition. This study emphasized the demand for dedicated gravitational wave data analysis techniques to detect postmerger gravitational radiation. Towards this goal the theory group has provided gravitational wave templates for a study with simulated injections assessing the prospects for equation of state constraints from gravitational wave measurements [Haster, C.-J., Chatziioannou, K., Bauswein, A., Clark, J.-A.; Inference of the Neutron Star Equation of State from Cosmological Distances. Physical review letters 125, 261101 (2020) DOI:10.1103/PhysRevLett.125.261101].

Recent studies have shown the important role of nuclei around N=50 for the description of electron capture processes relevant for the collapse of massive stars leading to a core-collapse supernova. Based on the thermal quasiparticle random phase approximation, we shown that finite temperature effects are fundamental to overcome the Pauli blocking of the Gamow-Teller strength in the direction. Hence, N=50 nuclei do not represent an obstacle to electron capture during supernova collapse [A. A. Dzhioev, K. Langanke, G. Martínez-Pinedo, A. I. Vdovin, and C. Stoyanov, Unblocking of Stellar Electron Capture for Neutron-Rich N=50 Nuclei at Finite Temperature, Phys. Rev. C 101, 025805 (2020), DOI:10.1103/PhysRevC.101.025805]. Weak processes in which neutrinos are produced or emitted play a fundamental role for the evolution and nucleosynthesis in core-collapse supernova and neutron star mergers. We have advanced the description of neutrino processes in several fronts. We have developed a complete set of charged-current processes involving muons for supernova conditions [G. Guo, G. Martínez-Pinedo, A. Lohs, and T. Fischer, Charged-Current Muonic Reactions in Core-Collapse Supernovae, Phys. Rev. D 102, 023037 (2020), DOI:10.1103/PhysRevD.102.023037]. This allowed to perform a first study of the muonization of supernova matter [T. Fischer, G. Guo, G. Martínez-Pinedo, M. Liebendörfer, and A. Mezzacappa, Muonization of Supernova Matter, Phys. Rev. D 102, 123001 (2020) DOI:10.1103/PhysRevD.102.123001] and of the role of inverse neutron decay in the evolution of proto-neutron stars [T. Fischer, G. Guo, A. A. Dzhioev, G. Martínez-Pinedo, M. Wu, A. Lohs, and Y. Qian, Neutrino Signal from Proto-Neutron Star Evolution: Effects of Opacities from Charged-Current–Neutrino Interactions and Inverse Neutron Decay, Phys. Rev. C 101, 025804 (2020), DOI:10.1103/PhysRevC.101.025804]. At densities below the saturation density, matter tends to develop in homogeneities that may affect the evolution of core collapse supernova. Depending on the conditions this may lead to the formation of light neutron-rich clusters. We have performed a systematic study of the role of light and heavy nuclear clusters in core-collapse supernova evolution and found that their impact in the evolution is minor [T. Fischer, S. Typel, G. Röpke, N.-U. F. Bastian, and G. Martínez-Pinedo, Medium Modifications for Light and Heavy Nuclear Clusters in Simulations of Core Collapse Supernovae: Impact on Equation of State and Weak Interactions, Phys. Rev. C 102, 055807 (2020), DOI:10.1103/PhysRevC.102.055807]. At intermediate densities matter tends to form the so-called pasta phases. We have performed large-scale calculations of pasta phases aiming to determine their impact on neutrino-transport. Our results show that the cross section for elastic coherent neutrino scattering is dramatically increased [B. Schütrumpf, G. Martínez-Pinedo, and P.-G. Reinhard, Survey of Nuclear Pasta in the Intermediate-Density Regime: Structure Functions for Neutrino Scattering, Phys. Rev. C 101, 055804 (2020), DOI:10.1103/PhysRevC.101.055804].

Kilonova observations have demonstrated that neutron-star mergers produce r-process nuclei. In this scenario, fission is expected to play a very important role. We have explored the impact of different fission barriers in the production of translead nuclei and their impact on the radioactive energy production at timescales relevant for kilonova emission [S. A. Giuliani, G. Martínez-Pinedo, M.-R. Wu, and L. M. Robledo, Fission and the r-Process Nucleosynthesis of Translead Nuclei in Neutron Star Mergers, Phys. Rev. C 102, 045804 (2020), DOI:10.1103/PhysRevC.102.045804]. Several chemical evolution studies have shown that neutron star mergers may have problems explaining observations at low metallicities, i.e. during the early times of Galatic evolution. This suggest that at low metallicities an additional r-process site may operate. We have shown that rare supernova explosions triggered by a hadron-quark transition operating at high densities and hence only reached in the collapse of very massive stars may constitute such a site [T. Fischer, M.-R. Wu, B. Wehmeyer, N.-U. F. Bastian, G. Martínez-Pinedo, and F.-K. Thielemann, Core-Collapse Supernova Explosions Driven by the Hadron-Quark Phase Transition as a Rare r -Process Site, Astrophys. J. 894, 9 (2020), DOI: 10.3847/1538-4357/ab86b0]

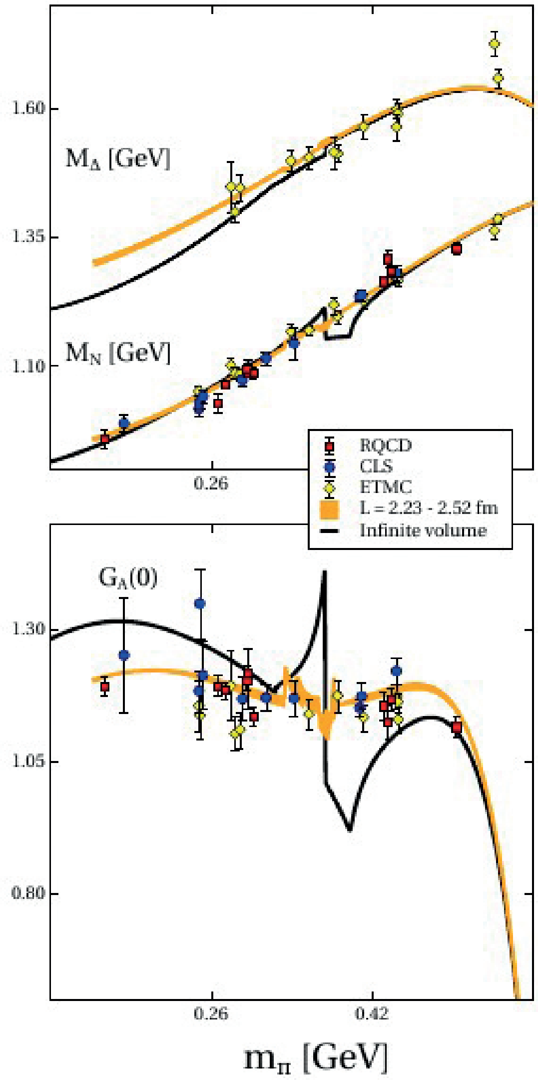


Figure 52. Nucleon and isobar masses and the axial-vector form factor of the nucleon as function of the pion mass compared tot he QCD lattice data. The orange lines are our result for the indicated rande of lattice sizes, the black lines are our predictions in the infinite-volume limit. Figure: M. F. M. Lutz, U. Sauerwein, R. G. E. Timmermans, The European Physical Journal C, volume 80, 844 (2020), DOI:10.1140/epjc/s10052-020-8417-5, ccby4

We consider the chiral Lagrangian with nucleon, isobar, and pion degrees of freedom. The baryon masses and the axial-vector form factor of the nucleon are derived at the one-loop level. We explore the impact of using on-shell baryon masses in the loop expressions. As compared to results from conventional chiral perturbation theory we find significant differences. An application to QCD lattice data is presented. We perform a global fit to the available lattice data sets for the baryon masses and the nucleon axial-vector form factor, and determine the low-energy constants relevant at N3LO for the baryon masses and at N2LO for the form factor. Partial finite-volume effects are considered. We point out that the use of on-shell masses in the loops results in non-analytic behavior of the baryon masses and the form factor as function of the pion mass, which becomes prominent for larger lattice volumes than presently used (see Figure 52).

Outlook

In 2020 the ERC Advanced Grant "Probing r-process nucleosynthesis through its electromagnetic signatures (KILONOVA)" was awarded with Gabriel Martínez-Pinedo as PI. This will allow to further strengthen the activities in the theory department related to the nucleosynthesis of heavy elements by the r-process. This project aims to improve the description of neutrino processes in neutron star mergers and the theoretical description of neutron-rich nuclei to be able to connect nucleosynthesis predictions with future kilonova observations.

Several projects lead by members of the theory department have been awarded within the recent call of the Helmholtz Forschungsakademie Hessen für FAIR. The focus this projects is to provide theory support for FAIR phase-0 experiments. In particular, we aim to exploit the unique possibilities of FAIR phase-0 to access r-process nuclei around N=126 and further constraints the theoretical description of these nuclei. Another project aims at the quantitative prediction of dileptons for calculations with and without a first order QCD phase transition.

Three members of the theory department —Andreas Bauswein, Hannah Elfner, and Gabriel Martínez-Pinedo— are PIs of the recently funded Cluster Project ELEMENTS by the state of Hesse. Our work within these project aims to connect equation of state models with constraints from experimental work, e.g. Hades and CBM in the future and to provide predictions of spectral energy distributions to be benchmarked against future kilonova observations.

Selected publications of 2020

- [1] Bauswein, A. ; Blacker, S. ; Vijayan, V. ; et al: Equation of State Constraints from the Threshold Binary Mass for Prompt Collapse of Neutron Star Mergers. Physical review letters 125(14), 141103 (2020), DOI:10.1103/PhysRevLett.125.141103
- [2] Haster, C.-J. ; Chatziioannou, K. ; Bauswein, A. ; et al: Inference of the Neutron Star Equation of State from Cosmological Distances. Physical review letters 125(26), 261101 (2020), DOI:10.1103/PhysRevLett.125.261101
- [3] Giuliani, S. A. ; Martinez Pinedo, G. ; Wu, M.-R. ; et al: Fission and the r -process nucleosynthesis of translead nuclei in neutron star mergers. Physical review / C 102(4), 045804 (2020), DOI:10.1103/PhysRevC.102.045804
- [4] Mohs, J. ; Ryu, S. ; Elfner, H.: Particle production via strings and baryon stopping within a hadronic transport approach. Journal of physics / G G, Nuclear and particle physics 47(6), 065101 (2020), DOI:10.1088/1361-6471/ab7bd1
- [5] Song, T. ; Moreau, P. ; Aichelin, J. ; et al: Exploring non-equilibrium quark-gluon plasma effects on charm transport coefficients. Physical review / C 101(4), 044901 (2020), DOI:10.1103/PhysRevC.101.044901
- [6] Lutz, M. F. M. ; Sauerwein, U. ; Timmermans, R. G. E.: On the axial-vector form factor of the nucleon and chiral symmetry. The European physical journal / C 80(9), 844 (2020), DOI:10.1140/epjc/s10052-020-8417-5

7. Report of the ExtreMe Matter Institute EMMI

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

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

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

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

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

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

An EMMI Rapid Reaction Task Force Meeting on "Direct reactions and nuclear structure" was held in July - August 2018 at the Lichtenberghaus, Darmstadt. The studies and discussions initiated during that meeting have led to a review article by participants of the RRTF published in 2020. The article discusses the present status of direct nuclear reactions and the nuclear structure aspects one can study with them. It discusses the spectroscopic information one can assess in experiments involving transfer reactions, heavy-ion-induced knockout reactions and quasifree scattering with (p,2p), (p,pn), and (e,e'p) reactions. T. Aumann et al, Quenching of single-particle strength from direct reactions with stable and rare-isotope beams, Prog. Part. Nucl. Phys. (2021) 103847 [arXiv:2012.12553 [nucl-th]]

EMMI Events in 2020: EMMI Workshop "Nuclear equation of state and neutron stars", Organizers: A. Bauswein, K. Hebeler, G. Martinez-Pinedo, A. Schwenk, January 12-18, 2020, Hirschegg, Austria, and ECT*-EMMI/GSI Workshop "Determination of the Absolute Electron (anti)-neutrino Mass", Organizers: L. Gastaldo, K. Valerius, February 10-14, 2020, ECT*, Trento, Italy

8. Activities at the department Detector Laboratory

Head: Dr. Christian Schmidt, GSI
Authors: C. Caesar, M. Deveaux, M. Kis, O. Kiselev, P. Koczon, N. Kuzminchuk, C. Nociforo, C .J. Schmidt, B. Voss, A. Wilms

The GSI detector laboratory DTL is a scientific technological department that aligns engineering competence, technical expertise, and scientific technological know-how on one side with modern equipment and fabrication facilities on the other. The combination allows the department to join-up with scientific collaborations towards the realization of complex detector systems and instrumentation for research at GSI and FAIR. The activities are aligned with the needs of the future project FAIR as well as the Helmholtz POF program Matter and Technologies.

The detector laboratory is engaged in all four pillars of FAIR, but with predominant involvement in CBM and in particular the development and production of the CBM Silicon Tracking Station (STS) as the largest single GSI in-kind contribution to a FAIR experiment. The activities are typically realized in close cooperation with the responsible members of the collaboration. The involvement covers the lead on the detailed mechanical layout and design of the STS as well as the development of STS detector module assembly procedures and tools. It further comprises the development of the quality assurance concepts and procedures for the construction of the STS and in particular for the assembly of detector modules as monolithic micro-assembled entities. Finally, towards serial assembly of the STS (876 modules), the detector laboratory developed the corresponding data logistics and follows-up on the Quality Assurance (QA) and Quality Control (QC) procedures. The concept of QA and QC procedures, including the tools developed for this purpose, was successfully presented to the FAIR Expert Committee Experiments (ECE) in October 2020. The development activities could be finalized together with the CBM-STS team through the FAIR Phase-0 engagement at mCBM and finally through the successful engineering design review at the end of the year, so that now the team may turn towards serial production and the practical organization at three assembly sites, namely IPE of KIT, JINR and GSI.

Also, the detector laboratory is engaged in the development of the powering and biasing scheme for the STS from concept to detailed engineering. This is an expertise that proved useful for other CBM-subdetectors as well as other experiments such as e.g. BM@N at JINR in Dubna, Russia. With this goal a mathematical model for low voltage powering was refined so that it allows for decisions concerning cross-section of conductors, maximum cable lengths, connector types as well as cable types. A new layout for installation of the power distribution infrastructure inside the STS-box, separating power from data readout, has been developed and prototyped in a mock-up for one STS-unit. Finally, a first conceptual study of a patch panel outside the STS but close to the detector for power cables, DAQ readout fibers and cooling installation has been worked out.

The technological developments for the CBM-STS can be employed in other experiments such as BM@N at JINR but also STRASSE of TU-Darmstadt at RIKEN. To fully exploit such synergies, DTL collaborates with both experiments. This potential was acknowledged by BMBF and resulted in considerable additional funding for the engagement in NICA experiments within the German Russian Roadmap for the years to come.

DTL continues to support GSI and FAIR experiments by assisting in the design and construction of diamond detectors from raw CVD-diamond material. High radiation tolerance and high temperature operation without cooling are key features in the devices developed for Super-FRS (see F. Schirru et al. 2020 J. Inst. 15 C04040, Evaluation of the counting efficiency of a pcCVD diamond detector irradiated by 62MeV/nucl. carbon beams). In particular, the conceptual design of the Super-FRS beam intensity monitor PDC, which the diamond detector is part of, together with its drive and the interface to the robot handling have been approved. Excellent time resolution was imperative for the application of diamond detectors at CRYRING also. Further, DTL supports HADES in their effort to transit from diamond detectors to the novel silicon LGAD technology for the start detector (T0).

The infrastructure used in the cleanroom for the production of Scintillating Fiber Tracking Detectors was upgraded in 2020 considerably. To this end the existing large-frame wire winding machine was extended with a dedicated fiber station which allows to align planes of fibers to form fiber ribbons. As an example, fiber tension may be fine-tuned and recorded during production. Furthermore, soft- and hardware was developed to build a fiber sorting station. Using this station, the fibers can be sorted into a fiber mask along a pre-defined scheme, which is essential to reduce the number of readout channels while maintaining high spatial resolution. This setup allows to assemble and verify the correct sorting of the fibers. For this purpose, Raspberry Pi (Rasperry Pi is a trademark of the Rasperry Pi foundation) computers were equipped with TFT displays and mounted on the fiber fan-out. The EPICS based software allows to switch light on and off for each individual pixel in order to guarantee the correct order while sorting the fibers into the mask. Currently one detector based on fibers of 250 x 250 µm2 cross section is built. The active area amounts to 10 x 10 cm2. It is a double layer detector to determine x and y position.

Furthermore, four large area detectors (50 x 50 cm^2) are built from 1mm square shaped fibers. These detectors will be employed at the R3B experiment.

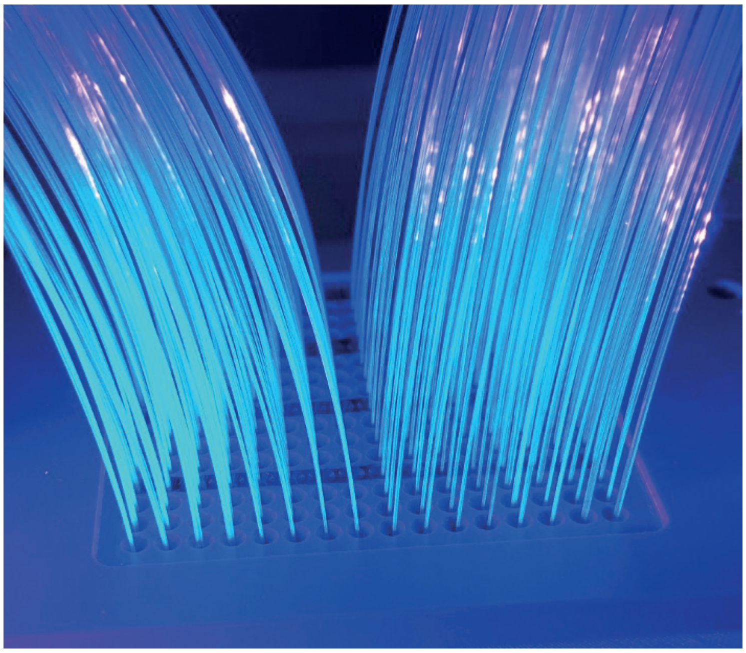


Figure 53. Tool for sorting of scintillating fibers. Each fiber can be illuminated computer controlled so that its correct allocation on both ends may be verified. The technique allows the efficient production of large size fiber mats as tracking layers for one-dimension (photograph with curtesy by C. Caesar)

Intensive investigations on the overall concept of a high-pressure time projection chamber, acting as an active target at the R3B set-up, was carried out. The inner electrode structure and the front-end electronics were developed and tested in the lab with the aim to increase rate capability and the ability to handle a beam of heavy-ions. The reconstruction of the active target IKAR started, which was utilized at GSI for experiments with light exotic ions earlier. Commissioning of IKAR with a modernized detector is scheduled at CERN in 2021 with a beam of high-intensity.Also for R3B silicon micro-strip detectors were tested in a newly constructed set-up using cosmic rays. At the end of 2020 the detectors were installed in a two-arm configuration around the liquid hydrogen target for the experiments measuring (p, 2p) reactions within the R3B FAIR Phase-0 program, scheduled for 2021. New silicon micro- strip detectors with larger active area and higher readout speed are being developed in collaboration with INFN Perugia.

For the Super-FRS collaboration, recently developed 64-channel front-end readout chips for time and charge measurement (from the company PetSys) were tested. In particular, they have been designed for the readout of multi-anode PMTs, providing time resolution down to 30 ps at high rates. These CMOS chips are quite compact and radiation tolerant so that they can be placed directly onto the detector. A new, scalable DAQ system for the readout of these chips was tested. A set-up with 512 channels has been prepared for the test of a prototype of the Super-FRS scintillating fiber based neutron detector.

A very compact 'Travel-Multi Sampling Ionisation Chamber MUSIC' has been developed, built and successfully tested at FRS in 2020. It comprises 10 electrode-pairs of approximately 200mm width and 40mm in beam direction, each subdivided in a pair of backgammon-like structure and read out by individual channel electronics. In the future it will serve as a basis for further MUSIC developments for FRS as well as the Super-FRS facility in future where it will serve as a part of the 'standard' beam-diagnostics equipment. The latter will make use of higher integrated readout electronics, commercially available as a full DAQ chain which is under development in close collaboration with industrial partners.

In the field of medical and biological applications, previous detector developments for the control and operation of heavy-ion beam therapy and irradiation could be continued and improved in Cave-M. Proof-of-principle measurements with the new Tera09 multi-channel electronics were performed successfully ["Design and characterization of a 64 channels ASIC front-end electronics for high-flux particle beam detectors.", F. Fausti et.al; NIM A 867 (2017) 1–6].

A demonstrator system for the future Planar GEM-Tracker detector to be installed in the target spectrometer of the PANDA experiment has been developed and assembled. It is employing several key-technologies for validation purpose. It offers particle tracking on an active area of 400x400 mm^2 at two planes in a back-to-back configuration, thus four independent coordinates with approximately 4000 channels with a granularity of 400 µm aiming for a positional resolution of 150 µm with only minimal material budget (<0.5% X_0) at particle rates of up to 140 kHz/cm^2. The detector system will employ two GEM-stacks with 3 GEM-foils each in front of each of the projection planes.

For the future Collector Ring (CR) at FAIR within the ILIMA collaboration (Isomeric beams, LIfetimes and MAsses) the masses of short lived nuclides will be measured with Isochronous Mass Spectrometry (IMS). The masses of exotic nuclei can be deduced from a precise measurement of the revolution time by means of two Time-of-Flight detectors placed on the straight section of the ring. The main goal of the new system is to measure the particle speed of the individual ions in addition to the revolution. Within the framework of the ILIMA experiment, the design of a new dual Time-of-Flight detector system for CR has been finalized based on the versatile developments and improvements of the existing ESR-TOF detector. The Time-of-Flight detectors for ILIMA are a GSI in-kind contribution and the in-kind contract was signed in May 2020.

For FAIR beam monitoring in the high-energy beamlines, a particle detector combination composed of a current-grid and an ionization chamber providing intensity as well as positional information on an area of 100x100 mm^2, which has been developed in the past is now in serial production at DTL. A total of 40 systems will be supplied as a German in-kind contribution to FAIR.

Finally, DTL managed to liberate resources which allow to engage in future oriented detector technologies. In view of the CBM silicon tracking station going into serial assembly, in view also of further future silicon tracking needs such as for example the R3B highly granular silicon tracker, DTL engages in CMOS pixel sensor technology and its integration. With a new scientific position granted and additional funding obtained within the EU-Project CREMLIN-Plus there is considerable potential for impact in the field. Together with the ALICE group and University Heidelberg a beam telescope based on the ALPIDE silicon CMOS pixel sensor developed at CERN was taken into operation. A test station dedicated to this activity was organized at the detector laboratory. Several beam tests at GSI and DESY were performed leading to important experience needed for further developments of these detectors and their applications. Conceptual development of a larger size detector started in cooperation with Super-FRS, R3B at FAIR, and the AMBER collaboration at CERN.

In 2021, the laboratory will focus in on the preparation of serial assembly and production for various detector projects.

Selected publications of 2020

- [1] Bäni, L. ; Alexopoulos, A. ; Artuso, M. ; et al: A Study of the Radiation Tolerance of CVD Diamond to 70 MeV Protons, Fast Neutrons and 200 MeV Pions. Sensors 20(22), 6648 (2020), DOI:10.3390/s20226648
- [2] Pietraszko, J. ; Galatyuk, T. ; Kedych, V. ; et al: Low Gain Avalanche Detectors for the HADES reaction time (T0) detector upgrade. The European physical journal / A 56(7), 183 (2020), DOI:10.1140/epja/s10050-020-00186-w
- [3] Schirru, F. ; Nociforo, C. ; Schlemme, S. ; et al: Evaluation of the counting efficiency of a pcCVD diamond detector irradiated by 62 MeV/nucl. carbon beams. 15th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, Italy, 14 Oct 2019 - 17 Oct 2019 Journal of Instrumentation 15(04), C04040 - C04040 (2020), DOI:10.1088/1748-0221/15/04/C04040

9. Research of the Department IT

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

The IT Department provides and develops the IT infrastructure of GSI and FAIR. Large-scale IT-systems for all business units are operated together with the relevant departments of GSI and FAIR. The department also develops, together with national and international partners, advanced software and services for the various and unique requirements of nuclear and high energy physics experiments.

Highlights in 2020

New Virgo Cluster

A new HPC (high performance compute) cluster Virgo has replaced its predecessor Kronos which was in production from 2015 until end of 2020. The Virgo cluster was made available to selected users as pre-production system in June 2020 and entered production in August 2020. The system provides Virtual Application environments (VAEs) based on Linux container technology to enable multiple different user environments on a single host platform [see, https://hpc.gsi.de/virgo]. Besides the VAEs supported by IT, it is possible for users to launch custom build containers as well. The capabilities of the workload management system have been adapted to allow flexible partitioning of resources. This is particularly useful in order to dynamically orchestrate groups of compute nodes upon requests for online-computing resources by different scientific experiments.

Online Cluster Controller for mini CBM and ALICE

In preparation for the beam times at the GSI in 2021, and especially for mini-CBM, a cluster controller based on the Online Device Control (ODC) package [see, https://github.com/FairRootGroup/ODC] was implemented and tested on a dynamically allocated part of the GSI generic batch farm (Virgo). The ODC is also used as base for the online cluster controller by the ALICE collaboration at CERN. The major development in this package, this year, was the introduction of the so-called partitions; i.e.: running different parts of the farm for different detectors separately or different purposes with one ODC controller (e.g.: Calibration on one part and reconstruction and/or quality assurance on other part(s)).

Runge Kutta based fragment tracker

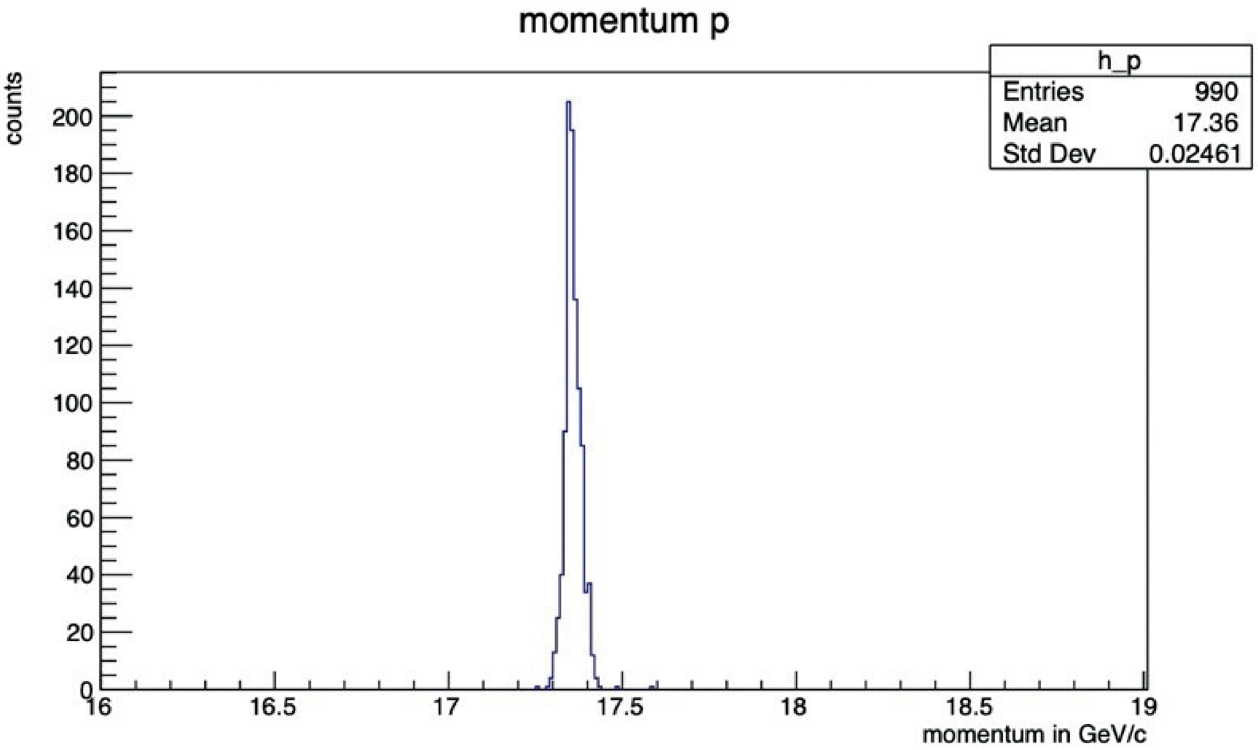


Figure 54. The tracked momentum of the primary beam directly from SIS18. A momentum resolution of 0.14% was measured. The fact that accelerator delivers about 0.1% resolution shows how precise the tracker is.

Together with the scientists from the Nuclear Reaction department, a new Runge Kutta based fragment tracker for the Reactions with Relativistic Beams experiment (R3B) was developed. The al-gorithm can be used on both simulated and real data, and also for the detector alignment. An exam-ple of the application of this algorithm is shown in Figure 54.

Selected publications of 2020

- [1] Al-Turany, M. ; Rybalchenko, A. ; Klein, D. ; et al: ALFA: A framework for building distributed applications. 24th International Conference on Computing in High Energy and Nuclear Physics, CHEP 2019, Adelaide, Australia, 2 Nov 2019 - 3 Nov 2019 The European physical journal / Web of Conferences 245, 05021 (2020), DOI:10.1051/ep-jconf/202024505021

10. IKP Jülich Progess and Achievements

Heads: Prof. Dr. James Ritman (FZJ & GSI), Prof. Dr. Hans Ströher (GSI),
Dr. Ralf Gebel (FZJ & GSI)

Excerpt from the IKP-Annual report prepared by Frank Goldenbaum,
Dieter Grzonka and James Ritman, Berichte des Forschungszentrums Jülich 4427,
2020, http://hdl.handle.net/2128/28809

Within the framework of the TransFAIR process, the scientific activities of the IKP Jülich - with the exception of IKP-3 - will be transferred in a stepwise procedure until end of 2027 to GSI Helmholtz-zentrum für Schwerionenforschung in Darmstadt. A cooperation agreement between Forschungs-zentrum Jülich (FZJ) and GSI, which came into force on 1 January 2021, regulates the collaboration between the two research centers until this time.

As a result, GSI is now responsible for the scientific research at IKP, and to ensure that the internationally recognized expertise of IKP in the fields of accelerator, hadron, and precision physics are available for the German science community.

The responsibility for the COSY operation will stay at FZJ until its decommissioning which is planned for end of 2024. Currently, the use of beamtime at COSY is jointly approved by the managements of GSI and FZJ, and the open sessions of the fall 2020 COSY beamtime advisory committee meeting was opened to all members of GSI. IKP has been actively collaborating with GSI for a long time within the framework of FAIR. For example, IKP-4 is developing and procuring components for the high-energy storage ring HESR. The installation and commissioning of HESR in Darmstadt will take place following completion of the buildings. The storage ring components have been designed, fabricated, and prepared for installation. The PANDA (Antiproton Anihilation at Darmstadt) detector which is one of the large-scale experiments for FAIR will be the key instrument for detailed studies in the field of hadron physics at FAIR at the HESR storage ring. This complex detector system will enable precise investigations into the structure and dynamics of hadrons in systems with strange and charm quarks as well as many-quark states, which are produced during the annihilation of high-energy antiprotons with protons or atomic nuclei. IKP is responsible for the fabrication of essential components for the detector system, including parts of the MVD, STT, computing framework and input for the luminosity normalization.

The following brief summary is a selective, strongly condensed version of the 2020 IKP-Jülich Annual Report as input to the 2020 GSI-FAIR Annual Report. For a more detailed description of the highlights and achievements of IKP in 2020 please refer to reference [1]. The full report contains more detailed information on:

- progress and achievements on experimental activities for FAIR including Phase-0
- research on storage ring based EDM search
- neutrino physics activities
- details on accelerator research including the progress of HESR
- highlights of the Theory Group
- and also some general information like publications, organized conferences of project funding.

Experimental Activities for FAIR

The design and the production of the main tracking detector of PANDA, the Straw Tube Tracker (STT), is one of the responsibilities of the IKP. First PANDA straw tube modules have been assembled and will be used in the FAIR Phase-0 experiment. They have been installed at the HADES experiment at GSI (see Figure 55 as the first Straw Tube Station (STS1) and successfully commissioned with a proton test beamtime. The STS1 consists of 704 straws arranged in four vertical double-layers with 0° and 90° azimuthal orientations. A double-layer consists of four modules, each with 32 straws, and one center module with 48 straws. All channels are working as planned and the system is ready for physics measurements that are scheduled in the upcoming year. A dedicated tracking algorithm for straw tubes based on a Hough transformation was developed. After the proof-of-principle in the previous year, the focus in this year was to improve its performance both in tracking quality as well as in speed.

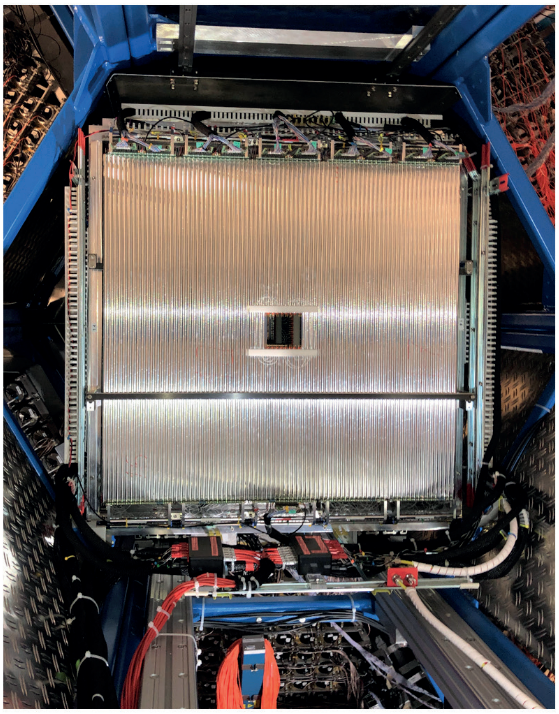


Figure 55. Photograph of the new Straw Tube Tracker Station STS1 installed in the HADES spectrometer.

Considerable progress was achieved with the KOALA experiment aiming at the measurement of differential cross sections of antiproton-proton elastic scattering in a wide range of four-momentum transfer squared, i.e., $|t|=0.0008\text{-}0.1\ (\mathrm{GeV}/c)^2$, which goes down to the Coulomb region. To validate the experiment proposal as well as the detector concept the KOALA setup was commissioned at COSY by measuring the proton-proton elastic scattering since both reactions have the same kinematics. It could be shown from the coincidence measurement between the recoil proton, measured with Si- and Ge- strip detectors, and the forward proton, measured with scintillation detectors, that the background events at lower t range can be significantly suppressed. The recoil protons can now be measured down to ~200 keV, which corresponds to about 0.0004 $(\mathrm{GeV}/c)^2$.

Further activities related to PANDA concern Monte Carlo studies. Detailed simulations on ΛK and the Ξπ decay of Ξ resonances with the PANDA detector in the reaction anti-p p-> anti-Ξ^+ +Ξ^{*-} and its c.c. channel were performed. A reconstruction efficiency of about 5% for anti-Ξ^+ + ΛK^- and 3.1% for anti-Ξ^+ + $\Xi^-\pi^0$ could be achieved. A major goal of the Ξ spectroscopy program within the PANDA research program is the determination of the spin and parity quantum numbers of the Ξ states.

Storage Ring Based EDM Search

For JEDI (Jülich Electric Dipole Moment Investigations), a calorimetric polarimeter based on inorganic LYSO scintillators has been built for use in a storage ring to search for electric dipole moments (EDM) of charged particles such as the proton and deuteron. Its development and first use was on the Cooler Synchrotron (COSY) at the Forschungszentrum Jülich with 0.97 GeV/c polarized deuterons, a particle and energy suitable for an EDM search. A couple of experiments were conducted at COSY in 2020 on JEDI polarimeter commissioning, proton Spin Coherence Time (SCT) studies / Snake commissioning, bunch-based spin phase-lock feedback system and optimization of the alignment of magnetic elements using spin tune. The EDM related experiments are intrinsically complicated and very difficult to perform. Setting up the machine, including the adjustment of all relevant beam parameters, orbit corrections, target setup, detector operations, Wien filter setup and tuning, and the chromaticity adjustments and measurements to ensure a long spin-coherence time, took most of the allocated time. An ambitious program has been initiated to enhance the beam diagnostics capabilities at COSY with respect to, e.g., beam position, machine tune, and chromaticity. Details on alignment campaigns of the COSY magnet system, improvements of COSY signals and distribution and the optimization of Rogowski BPM system are addressed in [1]. In view of the various technical challenges involved in building the final all-electric ring, as e.g., described in [CERN Yellow Report, arXiv:1912.07881], the CPEDM collaboration agreed to adopt a staged approach. A next step would be the design and building of a demonstrator ring for charged-particle EDM searches.

Neutrino Physics

A comprehensive geoneutrino measurement has been performed using the Borexino detector, located at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, resulting in a geoneutrino signal of about 47 TNU (terrestrial neutrino units). This corresponds to a total radiogenic heat of the Earth of about 38 TW (tera watt). The Borexino collaboration has also reported the direct observation of neutrinos produced in the CNO fusion cycle in the Sun. This was achieved after advances in the thermal stabilization of the detector and with a method to constrain the rate of radioactive contaminations in the scintillator. The neutrino group of IKP is also involved in activities at the Jiangmen Underground Neutrino Observatory (JUNO) being a multi-purpose, liquid scintillator-based neutrino experiment, originally proposed in 2008 to determine the Neutrino Mass Ordering by detecting reactor antineutrinos. The potential to measure low-energy solar neutrinos is currently under study and of particular interest to the neutrino group, thanks to the experience with solar neutrino physics in Borexino. Also atmospheric neutrinos, produced after Cosmic Ray interactions in the atmosphere, can be observed in JUNO. Since 2020, this topic is of particular interest of the IKP-2 group, in particular on the spectral and oscillation analysis. JUNO will also search for exotic phenomena, as non-standard interactions, sterile neutrinos, proton decay, and dark matter annihilation signals. The group activity includes also the development of clustering techniques for event reconstruction. JUNO liquid scintillator will indeed contain a non-negligible amount of the radioactive isotope ^{14}C, which cannot be removed due to its chemical similarity to the major isotope ^{12}C. Pile-up of these events can worsen the sensitivity to the neutrino mass ordering. Clustering algorithms aim to identify multiple events signatures inside one DAQ event and thus to remove the ^{14}C component. This studies lead to the development of a more precise vertex reconstruction algorithm.

Accelerator Research

During 2020 the efforts to improve beam diagnostics and control have been continued. Several new tools were developed and existing ones improved. By continuously migrating the systems to the control system EPICS, [EPICS], the advantage of its new capabilities was taken. The activities are driven by the needs of the operating crew as well as the requirements of the experiments. Details on the Control System Studio Upgrade, the EPICS alarm server and display, model calculations (MAD-X Model) as an integral part of accelerator research and operation, beam current monitor capturing, chromaticity measurements and the development of the Orbit Control software are described in the IKP Annual Report 2020 [1].

The JULIC cyclotron serves as injector for the storage ring COSY, accelerating polarised and unpolarised protons and deuterons to the injection energies of 45 and 75~MeV for the protons and deuterons, respectively. The maximum energies of the extracted JULIC beams are limited by the parameters of the cyclotron RF-system and extraction elements. In order to reduce the high voltage at the cyclotron electrostatic septum a new cyclotron mode of operation was developed in summer 2020 using a 55 MeV deuteron beam resulting in a significant stability increase of the cyclotron operation. Since September 2020 polarised and unpolarised deuterons of 55 MeV are injected into COSY.

IKP is leading the international consortium which is dedicated to build the HESR. It is strongly supported by colleagues from the Central Institutes for Engineering and Analytics (ZEA) of the Research Center Jülich. By the end of 2020 about 79 % (previous year: 68 %) of the total project investment money has been either spent or bound by contract. All planning is re-adjusted to deliver the pre-assembled HESR hardware components with the available personnel to FAIR as soon as possible to the storage hall or in time for the installation dates. Deliveries are planned to happen significantly before 31-12-2024. For details on the status of the work packages (magnets, power converters, RF-system, injection (kickers with pulsers), beam diagnostics, vacuum / space management, stochastic cooling and experiment integration) refer to [1].

Further Activities

Polarized HD Molecules have been realized, a polarized atomic beam source to produce nuclear polarized atomic hydrogen (H) or deuterium (D) beams has been used to polarize both isotopes independently at the same time.

The PAX-project development aiming to provide a method to produce an intense beam of polarized antiprotons was further pushed in a Joint Research Activity of the EU "STRONG2020" framework. Work packages include tests on the longitudinal spin-filtering at COSY ("SPINforFAIR"). In preparation of the longitudinal spin-filtering test, the first Siberian Snake commissioning beam time took place at COSY in March 2020.

An unexplored field of particle acceleration is the precession of particle spins in huge magnetic fields inherently present in relativistic plasmas. Laser-driven generation of polarized proton and ^{3}He-ion beams in combination with the development of advanced target technologies is being pursued by the group in the framework of the JuSPARC facility and the ATHENA consortium ("Accelerator Technology HElmholtz iNfrAstructure").

Reference

- [1] Goldenbaum, F. (Editor): Annual Report 2020. Forschungzentrim Jülich, Berichte des Forschungszentrums Jülich 4427, 2020, http://hdl.handle.net/2128/28809

11. Activities in Technology Transfer at GSI and FAIR

Head of the department: Dr. Tobias Engert
Authors: Tobias Engert, Yvonne Leifels

The Technology Transfer Department (TTR) is a staff unit reporting directly to the Administrative management. With 4.6 FTE, of which 2.6 FTE from third-party funding, the TTR is responsible for processing services and contract research, innovation management, business development and business development and technology marketing.

Transfer strategy

A transfer strategy with defined goals and measures was developed during the reporting period. The task of knowledge and technology transfer comprises the transfer of scientific findings to the public in the sense of knowledge transfer, the education and dissemination of knowledge on relevant public issues, and the technical utilization and commercial exploitation of scientific results from research as well as technological developments from the operation of the facilities.

The following measures are available for this purpose: Transfer via information, cooperation, industrial property rights and other intellectual property, minds and start-ups. Active monitoring of success will be carried out by means of qualitative evaluation as well as regular evaluation and recording of quantitative benchmarks.

The GSI pursues three main goals in the transfer mission:

1. creating a culture of innovation by promoting an awareness and understanding for transfer options,
2. optimizing 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.

Activities

As part of a BMBF-funded initiative, Technology Transfer is developing a “Transfer Instrument for the Utilization of Waste Technologies from Large-Scale Scientific Projects”. The aim of the project is to improve the identification, safeguarding, further development and transfer of innovations from large-scale research infrastructure projects. The aim of the initiative is identification and exploitation of innovation at FAIR construction. Therefore, a Technology Liaison Officer (TLO) is installed. The project, funded with 900.000 Euro started in December 2018 and is scheduled to run for three years.

One of the first results from this project is the development of novel fuel cells/nano networks by forming microreactors from nanowire structural elements, where a fluid is passed through these structural elements and the nanowires act as catalysts for chemical conversions. Since these nanowire structural elements could also be advantageous for fuel cells due to their high specific surface area, a collaboration being established with the Zentrum für BrennstoffzellenTechnik GmbH (ZBT), Duisburg, in which a new type of KKS structure (cathode catalyst layer) will be developed for PEM fuel cells.

Furthermore, a feasibility study of a versatile simulation algorithm is funded: With the help of RoSEN (Robust (hyper)Surface Extraction Prodecures in N Dimensions), data sets of any dimension can be analyzed for similar data features. The resulting hyper-surfaces of identical feature characteristics are identified, visualized and described, such that the results can be used for versatile digital processing. The method was originally developed for the analysis of experimental data and the simulation of complex physical phenomena as they occur in the accelerator experiments at GSI/FAIR. Since February 2021, the feasibility study examines the use of RoSEN for potential process or product innovations in several technical-economically relevant fields of application, e.g.: the simulation of energy storage systems for regenerative energy supply, pharmacokinetic population modeling, industrial photogrammetry, with is used to digitize technical plants and buildings for computer-aided process or fault analysis, or for the use of multi-variant parameter spaces of business indicators to evaluate the economic performance of individual parts of companies.

Another project from the "Transfer Instrument for the Utilization of Waste Technologies from Large-Scale Scientific Projects" is a novel measurement method for detecting defects in underground cables and monitoring power networks. Within the scope of acceptance tests of the cable lines of the superconducting FAIR magnets, a measuring method was developed to detect faults in the cable, in the cable cross-section and in the connection plug without having to "open" the magnet. This measurement method for cable fault location and monitoring is being investigated, further developed and adapted to practical applications in cooperation with the southern Hessian energy supplier ENTEGA AG on their cables. A project plan is currently being developed to validate this technology.

Marketing activities of TTR

Transfer of competence to the industry: Green IT Cube / "DIGITAL OPEN LAB

The data center "Green IT Cube" built for FAIR has six floors with the capacity of 768 19" racks in principle. The floors already fully equipped contain 256 racks. The financing of the 3rd and 4th floors was recently applied for via the HMWK within the framework of the EU funding call REACT. In the DIGITAL OPEN LAB, innovations for energy-efficient high-performance computing, IT R&D software projects and ultra-fast data processing will be developed, tested and prepared for industrial application together with industry. So far, companies such as AMD, intel, Toshiba and HEAG - but also Darmstadt University of Applied Sciences - have expressed interest in the DIGITAL OPEN LAB. A contract is currently under discussion.

Beam time offer for industry

The irradiation with high energy ions is also interesting for companies of space industry, because they can test the radiation hardness of e.g. electronic components or utilized materials. Since about three years, more than twenty requests had to be rejected because of the accelerator upgrade. Due to this relatively large number of , there are currently considerations to assign industrial beam time, if a critical number of companies expresses their interest for 2022/23. For the development of a business model, the experiments for hardness tests have to be categorized in such a way that interesting service offers are created for industry.

Networking activities of TTR

European Network HEPTECH

In addition to the regional and national networking activities, TTR is involved in the European TT-Network “HEPTECH”- High Energy Physics Technology Transfer Network. HEPTECH was founded in 2008 as a part of th European High Energy Particle Physics strategy and currently comprises 16 international members such as CERN, ESS or ELI. Since December 2018, Dr. Tobias Engert, Head of the Technology Transfer Staff Office, is Chairperson of HEPTECH and Dr. Martina Bauer, also from the TTR staff office, is Network Coordinator. GSI competencies in Green IT were presented in the webinar “How High Energy Physics can contribute to Green Technologies?” organized by HEPTech at the international industry fair “Pollutec Fair-Green Days” at the end of 2020. Due to the pandemic, the topics Entrepreneurship and “HEPTrepreneurs” Episode 1 (Deep Tech Startups: Idea to Market) were prepared in the reporting year and carried out digitally in April 2021.

Network with local strong companies

As a continuation of the “Applied Quantum Conference”, which was held in February 2020 together with the local network partners ESA/ESOC, Merck KGaA and FAIR/GSI, the joint organization of another innovation conference was decided in the reporting period: “Darmstadt Symposium on Artificial Intelligence”. This event is planned in digital format from 5 to 6 October 2021.

Within the framework of the industry roadshows regularly held on campus, which serve the exchange with industry on new product developments or processes but also joint development work, only one event could be organized on campus due to the Corona pandemic. This was attended by two companies from Germany.

12. Executive summary to research & developments of the FAIR Project and specialized departments

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

Executive Summary

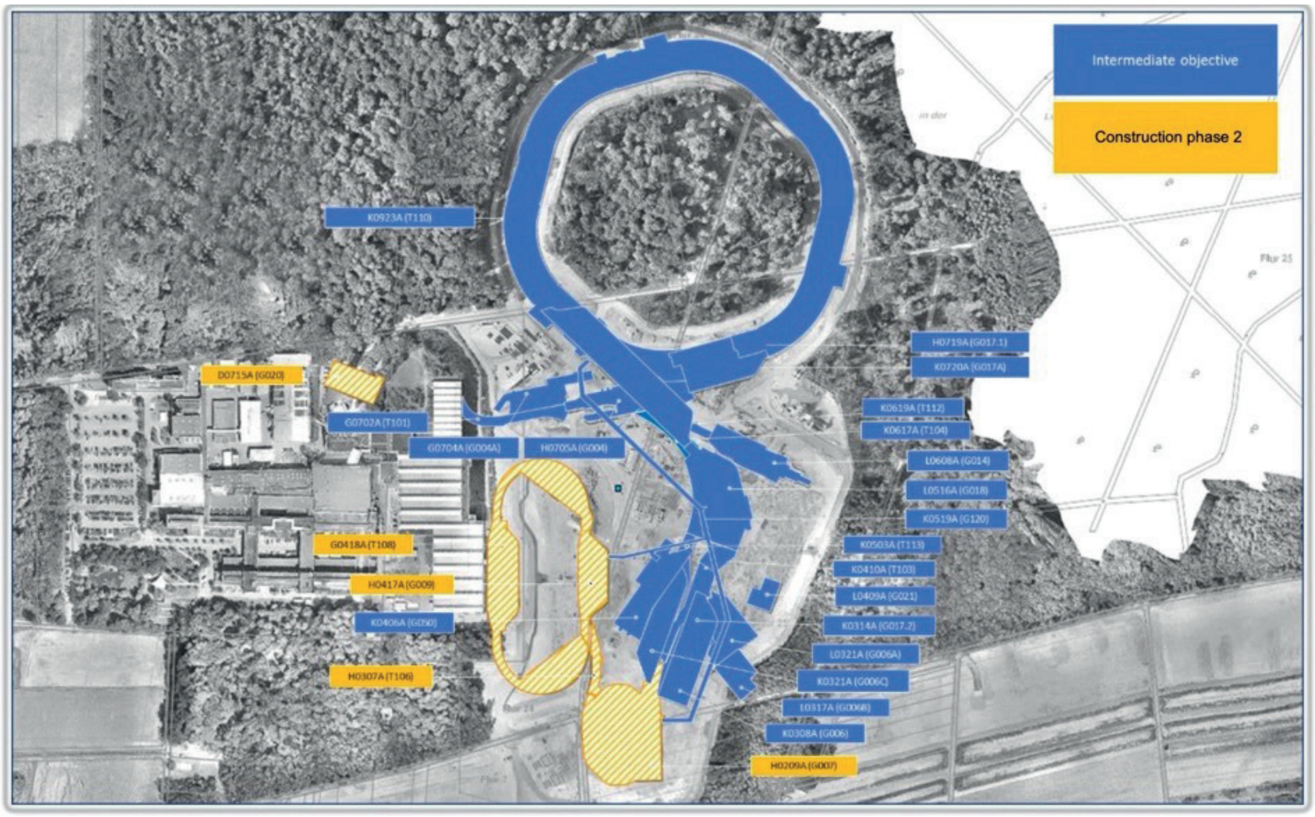


Figure 56. Overview of construction site “intermediate Objective” & Construction Phase-2.

According to the recommendation made by the “FAIR Project and Cost Review Board” in 2019 in the frame of an international review, the FAIR Council has finally given the official mandate to the FAIR management in February 2020 to realize the “Intermediate Objective” (IO) which includes the complete scope of the FAIR project except the buildings for the collector ring (CR), High-energy Storage Ring (HESR) and Proton-Linac (p-Linac). The necessary budget has been made available by Germany (BMBF) thus ensuring the continuity of the project execution. The clarification for the financing of the construction of the Modularized Start Version MSV of FAIR, progressed well in 2020 in the different countries according to their own budgetary process and regulations.

In line with the above decision, the second major contract for civil construction south has been awarded in April 2020 to the company ZÜBLIN. In the area of technical buildings installation, few contracts awards such as cranes and firefighting system have been finalized in the course of the year. The tendering process of the major technical buildings installation packages such as ventilation or heating and cooling, has progressed smoothly thanks to the availability of budget.

On the construction site, the excavation works for the SIS100 tunnel and the CBM building has been completed in July 2020. The civil works for the SIS100 tunnel and the transfer building could progress satisfactory despite of the COVID-19 pandemic and a major milestone has been reached in December 2020 when the ground slab ring of the SIS100 tunnel has been fully completed by the company PORR. The company ZÜBLIN has also mobilized its site infrastructure and organization starting in June 2020 so that the excavation works as well as the first concrete pouring could start in September 2020.

On the Accelerator side, the development of the machines is well advanced in many areas so that many contracts could be closed and production activities could progress satisfactorily, despite the COVID-19 pandemic. Significant progress and milestone achievements can be reported. Such as:

- the delivery of the first integrated SIS100 Quadrupole Doublet Module at GSI for testing
- the FAIR contract award for Super-FRS iron shielding to company Coswig (Germany)
- the successful Site Acceptance Test (SAT) at GSI for the CR Palmer pick-up tank (GSI in-kind)
- the signature of the GSI in-kind contract with company Demaco (NL) for the design, delivery and installation of the SIS100 cryo distribution system
- the signature of the FAIR in-kind contract with IOFFE Institute (Russia) for the Super-FRS Time of Flight (TOF) – Detectors
  the delivery of two SIS100 injection septa magnets by the company Danfysik for testing
- the delivery of the first bypass line for SIS100 Cryo
- the successfully Factory Acceptance Test (FAT) of the First of Series (FOS) long multiplet for SuperFRS at company ASG (Italy) and
- delivery to CERN for SAT the delivery of the last SIS100-Cryo- Catcher of the entire series production of 61 pcs

Experiments and FAIR Phase-0

Despite the Covid-19 pandemic the FAIR collaborations managed to achieve significant progress in 2020. The construction of experimental components proceeded reaching an overall progress of about 5%, with major highlights being: the delivery of the PRIOR-II magnets for APPA HED@FAIR, verification of the free-streaming concept for the DAQ system of CBM through experiments in FAIR Phase-0 with mini-CBM, delivery, testing and commissioning of several NUSTAR components, e.g. for DEGAS and R3B, delivery and testing of most fused silica bars for the PANDA Barrel DIRC, to name a few only. The restrictions imposed by the pandemic meant that the operation mode of the experiments in FAIR Phase-0 had to be changed on short notice to mostly remote operation with only few people on site. The fact that, nonetheless, overall, about 2/3 of the envisaged experiments could be performed with impressive scientific results can be considered a great success under those difficult circumstances.

12.1 Research & developments of the division SIS100/SIS18

Head: Dr. Peter Spiller

The installation of the new IPM (Ionization Beam Profile Monitor) in SIS18 has been completed. The new monitor enables turn-by-turn beam profile measurements, which will help to improve the understanding of beam dynamics phenomena and to further reduce beam loss.

By means of measuring the x-ray spectrum of the electrostatic extraction septum, the origin of the insufficient deflection angle at slow extraction of high energetic beams could be identified. In the past, this issue has driven significant beam loss and machine activation. With the replacement of the HV power converter, the nominal extraction angle could be reached. Further developments are needed to explore the general limits of electrostatic septa at high intensity heavy ion operation. The decision for manufacturing a new, prolongated septum will be taken based on the experiences gained with operation at nominal deflection angle in the present user run. The design of cryogenic inserts for the SIS18 collimator chambers has been completed. A prototype device is presently in production at ILK, Dresden. After laboratory tests, the set-up will be integrated in SIS18 for beam tests.

After implementation of more precise modelling of cold-warm transitions in the UHV system, a new quality of simulations became possible with the GSI STRAHLSIM code. The STRAHLSIM code has been developed to study the impact of technical measures on beam loss by charge exchange and the dynamics of the residual gas spectrum. For the first time, the simulations indicate that a sufficient transmission of low charge state heavy ions, at high repetition operation, consistent with the FAIR requirements, may be achieved. The benefit of cryogenic inserts has been studied.

SIS100 Status Report

Figure 57. Celebration of the completion of production and cold testing of the 110 SIS100 superconducting dipole magnets.

After completion of the full series production of the 110 superconducting dipole magnets by company Bilfinger Noell, Würzburg (Germany) (Figure 57), and after successful start of the series production of the dipole chambers, the integration process of both has been launched (Figure 58). About 60 dipole chambers, which is more the half of the overall series, have meanwhile been produced and delivered by the company PINK, Wertheim (Germany).

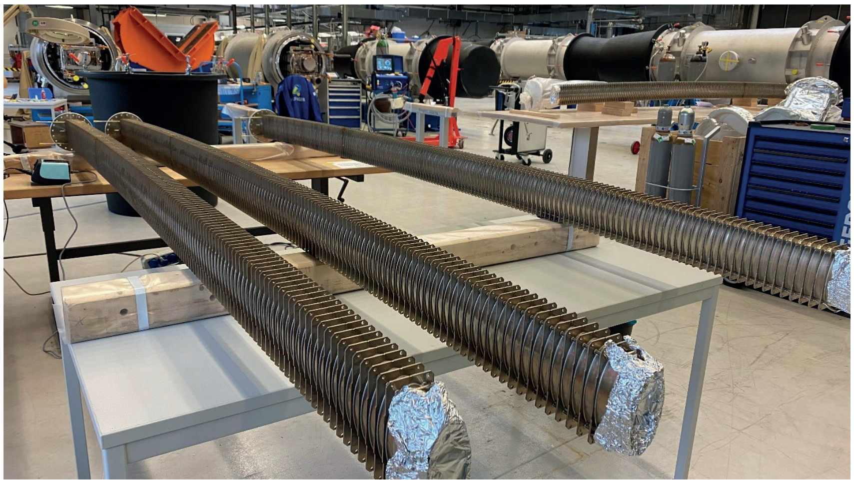


Figure 58. Integration of the thin wall, ripped dipole chambers (front) into the s.c. dipole magnets (back).

The integration takes place in the GSI testing hall, supported by Bilfinger Noell with respect to the hydraulic system and employees of external service companies with respect to the UHV system. After finishing the works for the dipole modules, the team at Bilfinger Noell has started working on the manufacturing of the missing dipole modules. In 2020, two types of modules had to be re-designed and equipped with an additional safety valve to cope with an improved safety concept for the hydraulic circuits. The production of the quadrupole unit series by JINR, Dubna (Russia) is still quite at the beginning. A first pair of units delivered to Bilfinger Noell for integration into quadrupole modules, has been accepted. Further eight units have been assembled and tested. Noticeable progress has been achieved in the quality and rate of unit assembly at JINR (Russia), such that the ramp up of series integration of quadrupole modules is now under preparation at Noell. In order to maintain the schedule, advanced production of several parts of the quadrupole modules has been released by GSI. Thus, many components have been produced and delivered by the subcontractors of Bilfinger Noell and are now in the storage areas. After successful cold testing of the FOS module, one further quadrupole module is presently in the integration process and will be completed in May 2021. This, module and the first of each type in the series production, will be cold tested with power at GSI. All other modules will be shipped to INFN, Salerno (Italy) for cold testing. The set-up and completion of the test facility at INFN Salerno is progressing well. Completion and commissioning is expected for July 2021.

After a first tender with no suitable commercial results, the procurement process of the main dipole- and quadrupole power converters could be re-launched. The technical and commercial evaluation of the new offers received has been completed.

Figure 59. Series of ferrite-loaded acceleration cavities in storage area Weiterstadt.

The assembly of the acceleration cavities at company RI, Bergisch Gladbach (Germany), and the corresponding power converters at company OCEM (Switzerland) could be completed. All cavity systems have been delivered to GSI and accepted (Figure 59).

After mitigating some issues with the UHV acceptance tests, the series production of the cryogenic Beam Position Monitors (BPMs) by the company Kyocera-Friatec (Germany) has been started. In parallel, the company Gigacomp (USA) is producing and delivering the signal cables for the BPM system. The series production of cryo-ion catchers has been completed. All systems have been delivered and accepted. The focus of the special installations team is now on the specification of the halo-and slow extraction collimation systems.

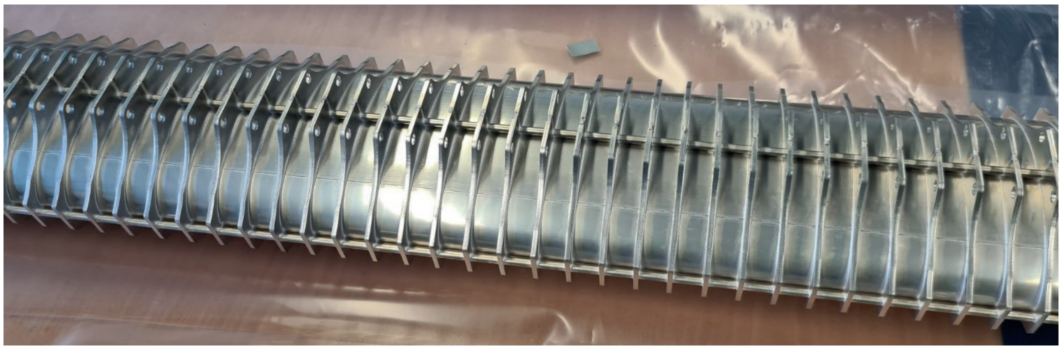


Figure 60. Thin wall, ripped quadrupole chamber with active LHe cooling and excellent manufacturing quality.

The soldering problems at manufacturing of the quadrupole chambers by company RI, Bergisch Gladbach have been solved, resulting in a high quality series production (Figure 60). Several chambers could be completed and delivered to company Bilfinger Noell for integration.

The required performance of the injection kicker system is still not reached. During pulsing, an increase of the residual gas pressure in the tank has been observed indicating HV discharges in the kicker system. Consequently, the kicker system has been send back to company Danfysik (Denmark) for a modification of the design of specific components. However, even after the revision, the specified pulse shape, especially the rise time, could not demonstrated. Further modifications and tests are planned. After it became clear, that a strong electrostatic quadrupole in the kicker modules may have impacted the beam dynamics, the design of the bipolar extraction kicker system had to be corrected. After a major modifications in the kicker design, the design phase is now approaching the Conceptual Design Report (CDR). After shipment to GSI, the Site Acceptance Test (SAT) including power tests of the two injection septum magnets and their power converters has been successfully completed. Also the fast quadrupole magnet delivered by company Sigma Phi (France) has passed the FAT and SAT.

The production of the bypass lines is performed as Polish inkind contribution at the company Kriosystems (Wroclaw) (Figure 61). The first delivered bypass line has been extensively and successfully cold tested at the GSI series test facility, STF. Further four BPLs are delivered to GSI.

However, the observations indicate that a careful fixation of the bus bar system operated with currents up to 17 kA required attention especially in the interconnection regions. Further bypass lines are in the assemble process at Kriosystem and will be delivered on short term. The design of the split feed-box is progressing well and is approaching the CDR phase. Due to changes in the current lead box design and an improved safety concept for the hydraulic system, the design had to slightly adapted.

Figure 61. Lifting of a bypass line at company Kriosystem (Poland) in preparation of the delivery to FAIR.

12.2 Research & developments of the division Super Fragment Separator

Head: Dr. Haik Simon

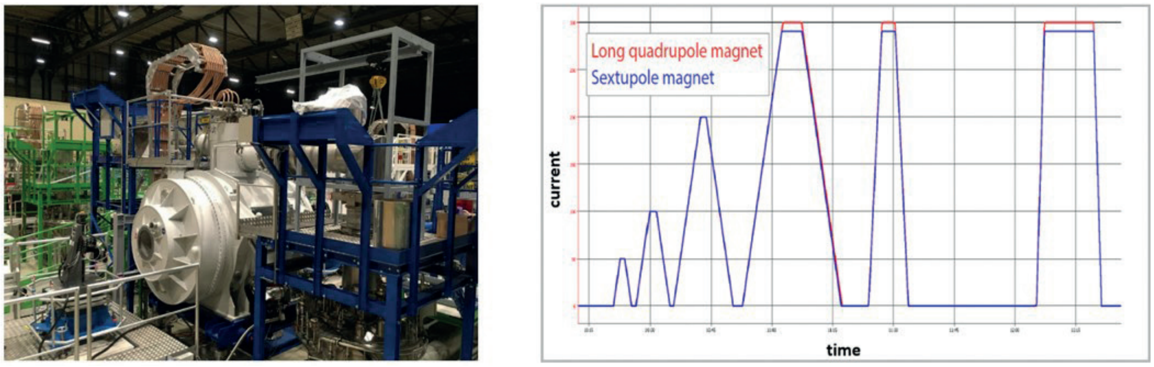


Figure 62. Left: FOS sc short multiplet at the testing station at CERN. Right: Parallel powering of the two magnets housed by the sc short multiplet.

The Super-FRS will be the most powerful in-flight separator in the world, and one of the few most powerful sources for exotic isotopes worldwide. It will provide clean and intense beams of unstable, short-lived nuclei, necessary to explore special properties of nuclides very far from the valley of stability. As a machine, the Super-FRS has to face several technological challenges, like the realisation of remotely controlled components with reliable performances in a highly radioactive environment, the super-conducting-magnet system allowing for large apertures, and the diagnostic systems with high rate capability.

The realisation of the Super-FRS has progressed in R&D, design, prototyping, production and testing during the whole 2020.

At the testing station at CERN, which was newly built to perform the SAT of superconducting (sc) magnets, the test of the FOS sc short multiplet was concluded. The multiplet is housing a long quadrupole and one sextupole. After the cool down, the full magnetic-measurement campaign was completed, results were in good agreement with simulations. The cryogenic tests was also successfully completed. The test result provided confidence in the good performance of the multiplet (Figure 62).

Figure 63. Left, middle: FOS sc long multiplet delivered to the testing station at CERN. Right: short (on the left side) and long multiplets (on the right side) on two testing benches.

The Factory Acceptance Test (FAT) of the FOS sc long multiplet – composed of one large quadrupole, three sextupoles, two short quadrupoles, two embedded octupoles, one steerer – was concluded on November 2020. The multiplet was delivered to the testing station at CERN on November 23 (Figure 63) to start its SAT. The short multiplet was moved to a second testing bench, which was successfully commissioned. A total of 32 multiplets are being produced by ASG, Genoa (Italy).

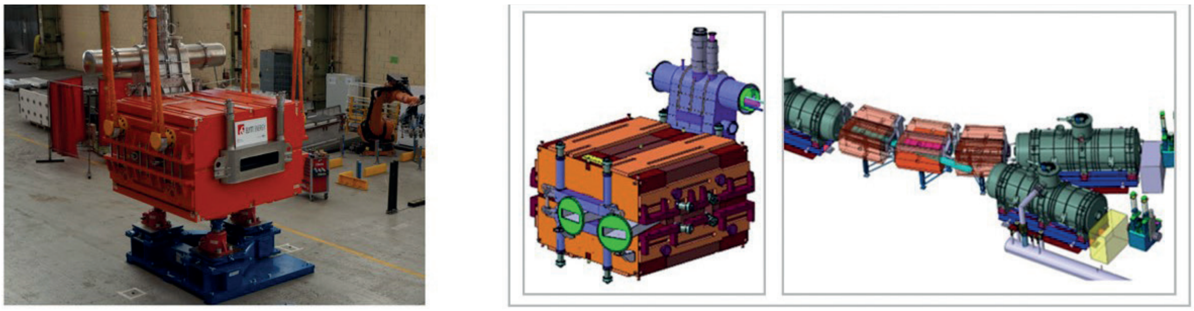


Figure 64. Left: FOS sc standard dipole at the factory. Right: Drawings of the sc branched dipole.

The FAT of the FOS sc standard dipole was concluded on the 11th of November 2020 by the manufacturer Elytt, Bilbao (Spain). Elytt is in charge for the production of 24 sc dipoles; three of them – the so-called branched dipoles – have a special Y-form to allow the forking of the beam into two branches. With the finalization of the conceptual design report (CDR) (October, 19) and the following final design report (FDR) (December, 14) the design of the sc branched dipoles is completed and Elytt started the purchasing phase (Figure 64).

The technological design concept for all components of the local cryogenics has yielded important progresses in 2020. The design report of the branch box, made by BINP, Novosibirsk (Russia), is advanced. The branch box is the starting point for distributing helium to the Super-FRS experimental branches. Most of the attached feed boxes, all jumper connections and transfer lines will be realised and installed by WUST, Wrocław (Poland), which is intensively working on the conceptual design report for the whole system in a collaborative effort.

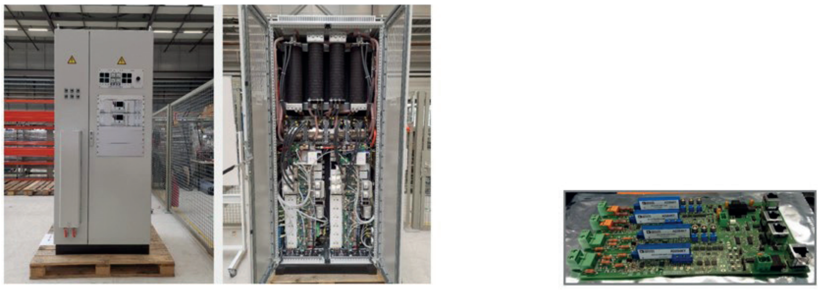


Figure 65. Left: Prototype of power converter. Right: Prototype of the quench detection/protection unit.

The manufacturing of a prototype of the power converters has been completed. On December 20, the company Jäger (Germany), delivered it to FAIR. First prototypes of the Quench Detection unit have been also produced and tested. The tests include the integration into the existing power-converter prototype on campus (Figure 65).

The normal conducting (nc) radiation-hard dipoles in target area are going to be built by BINP (Russia). The CDR was accepted on March 2, 2020. The radiation-resistant vacuum chambers of nc dipoles required a special R&D activity. The study and design concerned the integration of a radiation-hard shield (maybe titanium) into the chamber, acting as a primary beam disperser. In September, BINP presented the preliminary design review (PDR), with preliminary 3D-Model. BINP completed also the R&D of the nc quadrupoles and sextupoles, which will be located in the highly radioactive target area. Both dipoles and multipoles must be manufactured with special Mineral Insulated Cables (MIC) that are highly resistant to ionizing radiation.

Three beam catchers (or "beam dumps") are required to catch safely the unreacted primary beam after the target as well as a large share of the unwanted fragments. Because beam power is high, a direct beam must not hit a normal vacuum chamber but only the dedicated absorbers mounted inside the beam catcher chambers. The final design of the beam catchers was complete in March 2020. Beam catchers, nc magnets, and the target chamber will be surrounded by iron and concrete to shield the outside area from radiation. For this reason, all components in target area are placed in special alignment supports, holding up to 90 tons, which must be remotely adjustable to a sub-millimeter position and be resistant to high radiation doses. The study on these supports was concluded and the specifications were finalized in August 2020. The production of the lateral iron shielding blocks is progressing rapidly. The foundry Walzengießerei Coswig GmbH (Germany) released the CDR in July and the FDR in October 2020. In the meantime, in August, the specifications for the iron roof were also completed.

The progress in the R&D of the Super-FRS detectors is reported in this Scientific Report of the Detector Laboratory department. As far as the manufacturing design is concerned, the CDR of the time-of-flight (ToF) detectors, produced by the Ioffe Institute, St. Petersburg (Russia), was approved on November, 12. The specification for the 2 beam stoppers was approved on January 31, and the tendering processes ongoing.

12.3 Research & developments for the Proton and pbar Target

Head: Dr. Klaus Knie

Proton-Linac (p-Linac)

The ion source and the Low Energy Beam Transfer Line (LEBT) have been dismantled at CEA (France) and delivered to GSI.

The contract for SEM Grid was finalized and a first design was presented. The beam shape monitor was delivered. For the Bunch Shape Monitor BSM a first test with beam is planned in the 2nd quarter of 2021. The software development for integration of the BPM into the Front-End Software Architecture FESA has been started.

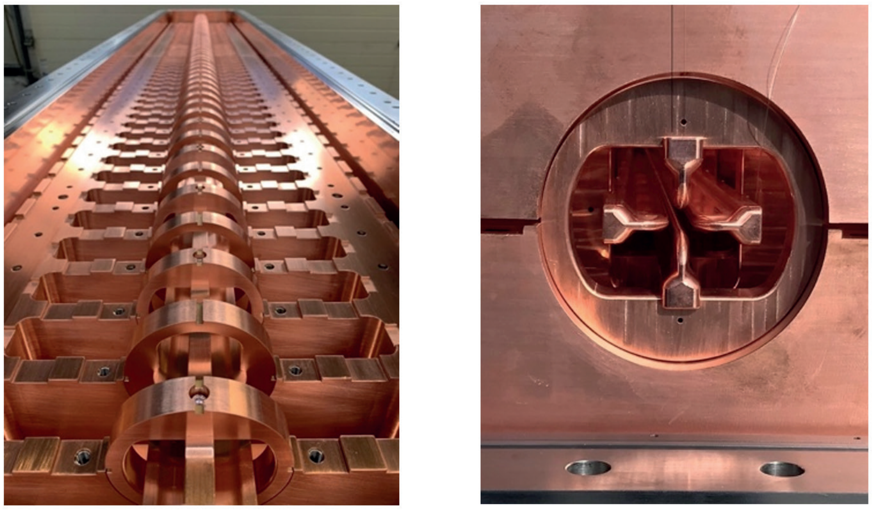


Figure 66. p-Linac ladder RFQ. Left: Tank opened and upper part of the ladder structure removed. Right: View in beam direction into the electrodes.

The commissioning without beam of the ladder RFQ (see Figure 66) is progressing. Plungers are under construction. After completion of the first modulator, power rf tests at GSI are scheduled for the end of 2021.

Figure 67. CH1 dummy before and after in-house copper plating.

The tendering process for the Cross-bar H drifttube and coupled CH cavities was completed. The first CH cavity will be ordered with the option to purchase all cavities. As a first step, the CCH1 tank will be delivered next year to perform low level rf tests. In parallel, copper plating test for these complex monolithic structures a progressing. A dummy of the first CH cavity was prepared for copper plating tests at GSI's galvanic workshop (see Figure 67).

Design and mechanical integration of the inter-tank sections, the MEBT and the diagnostic section is progressing. As an example, the MEBT section between RFQ and CH1 is depicted in Figure 68.

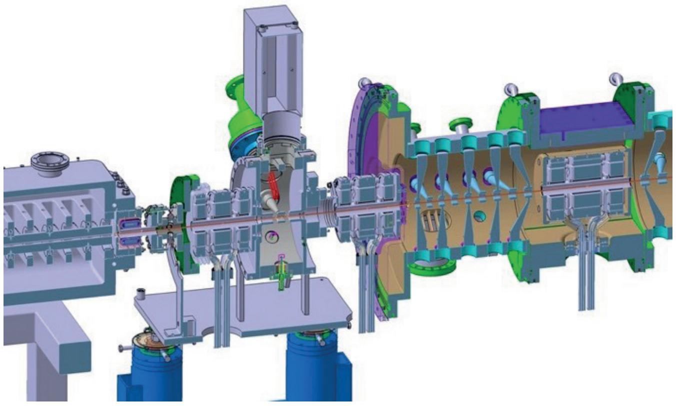


Figure 68. Inter-tank section (MEBT) between RFQ and CCH1.

pbar Target

The detailed specifications of the magnetic horn system are completed and the tendering can be started as soon as budget is available.

The ion optics of the pbar separator were re-examined together with BINP (Russia) resulting in transmissions close to 100 % for particles within the acceptance of the Collector Ring. Four positions for vertical and two positions for horizontal steerers were identified in the PS01 beamline between the target and the second dipole. Standard CR-type steerers with a maximum bending angle of 1.5 mrad will be used. Four standard CR sextupoles are provided to correct for chromatic effects.

In order to allow a timely production at BINP, most magnets will be very similar or even identical to those used in the Collector Ring. However, directly after the target special radiation resistant magnets have to be used. The supplier of the three radiation resistant quadrupoles is still under discussion. For the most critical magnet, the large dipole after target, at least a CR-type yoke produced by BINP can be used. If required, a coil with radiation resistant isolation and a special connection box will be tendered independently together with the quadrupoles.

The shielding flask for the transport of activated targets and horns will be contracted together with the Super-FRS flask. The work on the detailing of the remote-controlled exchange system for highly activated components (target, magnetic horn) is progressing.

12.4 Research & developments for the Collector Ring

Head: Dr. Ivan Koop / Dr. Oleksiy Dolinskyy

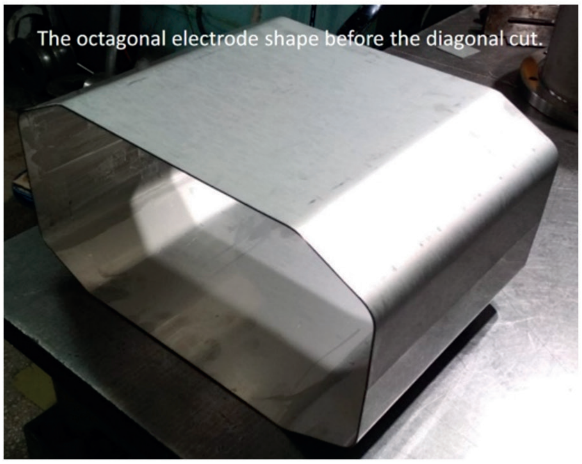
Figure 69. First of series CR dipole magnet assembled at BINP (Russia).

Design and production of the CR magnetic components is ongoing at BINP (Russia). A major achievement is the readiness of the FOS dipole magnet, which has been fully assembled and is ready for FAT (Figure 69). First magnetic measurements at an intermediate field of 0.8 T have been successfully done. For magnetic measurements at the nominal field of 1.6 T, a QPC-type power converter prototype (1500 A) is presently under construction and testing. After field measurements, the pole chamfering will be optimized to reach the required integrated field quality of ±1x10-4. Further fine-tuning of the field homogeneity will be possible by means of dedicated magnetic rods, which can be inserted into the poles to compensate the field deviations within the useable aperture of the magnet.

It is foreseen that all 24 dipole magnets in the CR will be equipped with the NMR probes for precise field measurements with the pulse method during operation. The system is designed to measure the absolute field strength in the range 0.5 – 1.6 T within 1 s. The specified relative precision and repeatability of the measurements is < 10 ppm. The NMR probes will be delivered by BINP together with the series dipole magnets for pre-assembly and SAT.

The Conceptual Design Report of the CR injection/extraction kicker system has been completed. The system will consist of two kicker tanks (six full aperture pulsed magnets in total) providing the required integrated field of 194.4 mT·m. Each magnet will be made of ferrite cores and will be powered by an individual power supply at the maximum current of 5.6 kA. The rise/fall time of the magnetic field has to be < 318 ns as defined by the bunch length of antiproton and heavy ion beams at injection/extraction. The construction of the kicker system has been started at BINP.

Technical design activities on the beam instrumentation components are progressing at BINP and ITEP (Russia). The CR has 19 BPMs, most of which are integrated into the vertical correctors (in arcs). The required measurement accuracy of the beam position is 5 mm for the first turn and 1 mm for closed orbit measurements. Technical design of the BPMs has been finalized and approved at BINP. The large aperture BPM electrodes have been re-designed aiming to improve mechanical stability and tolerances as well as the production efficiency. In Figure 70 the improved design of the electrode shape is shown.



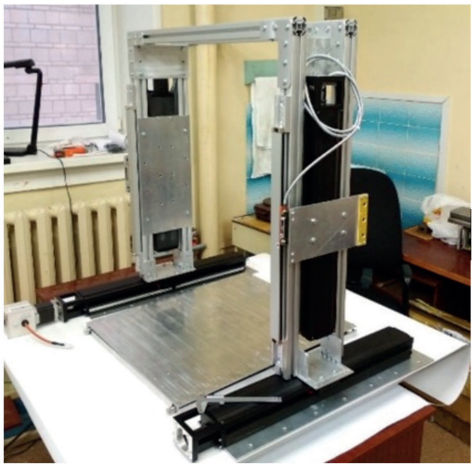


Figure 70. Testing sample of the re-designed octagonal BPM electrode (left) and the completed BPM test stand (right) at BINP.

Material procurement has been started in 2020. A dedicated BPM test stand (Figure 70, right) for mechanical and electrical testing has been completed and is under commissioning.

Figure 71. Mock-up installation for vacuum testing of the dipole and quadrupole/sextupole chamber assembly at BINP.

Prototype dipole and hexagonal quadrupole/sextupole chambers have been manufactured at BINP. A dedicated mock-up installation has been built (see Figure 71) to test and prove the vacuum system concept based on ISO-K flange connection with springy metal sealing. Vacuum testing implied the use of two pumping units, which roughly corresponds to the average pumping density in the ring. The pressure level of 2.3e-9 mbar has been successfully reached after 1 month of pumping.

The commissioning of the 2nd series RF de-buncher system has been started in 2020. The long-term operational reliability of the power supply units is still the focus and the major technical challenge of the SAT at GSI. A dedicated Electro-Magnetic Interference (EMI) study has been performed by the provider (OCEM) to understand a reason of sporadic shutdowns of the power supply due to the pulsed step modulation (PSM) operation during the commissioning phase. The most recent status overview of the development and commissioning of the CR de-buncher system can be found in [1].

Design and construction of the stochastic cooling system is ongoing at GSI and Forschungszentrum Jülich GmbH (Germany) [2]. Major part of the slotline pick-up sub-components is under procurement. The Palmer pick-up has been installed into COSY synchrotron at FZJ and will be tested within one of the planned beam time slots in 2021. A major decision has been taken that FZJ takes over the design and construction of the kickers in frame of the GSI-FZJ collaboration contract. This is an important step towards the completion of the stochastic cooling system in time according to the defined project baseline. The conceptual design of the kickers is progressing and the CDR review is under preparation.

References:

- [1] U. Laier et al., Status and recent development of FAIR ring RF systems, to be published in Proc. of IPAC21, Campinas, Brazil, 2021.
- [2] C. Dimopoulou et al., Development of Stochastic Cooling system for CR, to be published in GSI/FAIR Scientific Report 2021.

12.5 Research & developments for the High Energy Storage Ring

Head: Dr. Dieter Prasuhn

Figure 72. Components along the beam (left to right): Large pumping chamber 'fixed bearing', sextupole magnet, quadrupole magnet, beam position monitor with vacuum chamber extensions, sextupole magnet, small pumping chamber 'floating bearing'. All vacuum chambers or pipes are equipped with heating jackets. Turbomolecular pump attached to the pumping chamber 'fixed bearing' to allow immediate check of the vacuum assembly.

42 HESR main dipole magnets are stored in the intermediate storage area in Weiterstadt (Germany). In Jülich, 4 main dipole magnets are awaiting pre-assembly with the dedicated vacuum chambers with inlets and outlets for the laser beam of the SPARC experiment. The first quadrupole unit is being pre-assembled in Jülich. The process steps are being optimized for a reliable series assembly. After delivery to Weiterstadt, the accuracy of the alignment procedure before shipping will be re-evaluated.

After solving several technical issues together with the manufacturers the production and delivery of beam position monitors and ion clearing chambers is running continuously. For each beam position monitor the calibration coefficients are measured.

All sextupole and corrector magnets from the Romanian in-kind contribution to HESR are delivered. The delivery of the corresponding power converters from Romania is on-going according to schedule. The first 12 of these power converters are shipped to Weierstadt.

The RF cavities are being assembled in a clean room. Ferrite cores and amplifiers are already in Jülich. The work on the low level control system has started.

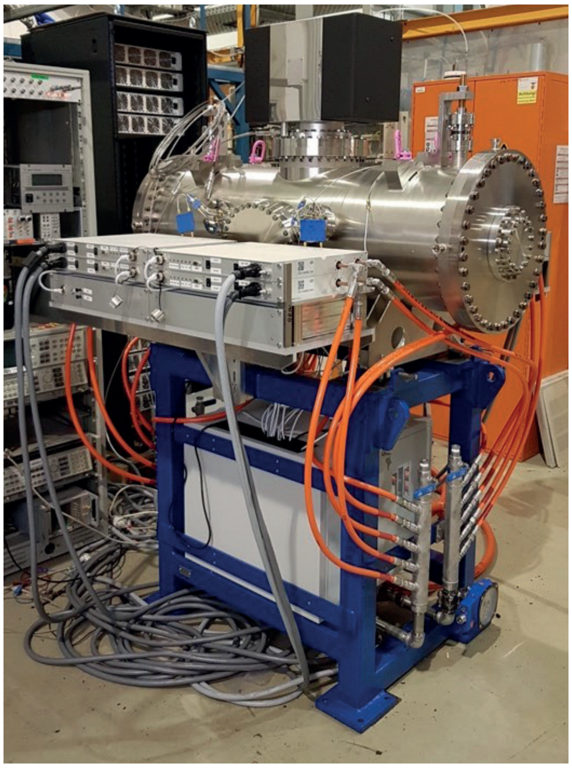


Figure 73. Stochastic kicker tank on girder. One half of the water-cooled high power amplifiers is visible, the other half is on the back.

Injection dipoles and injection septum including their power converters are delivered and stored in Jülich. The production of the injection kicker magnets and their pulse power converters is proceeding well. The required rise time of less than 220 ns has been achieved.

One complete system of the HESR stochastic cooling (Figure 73) is installed at COSY-Jülich and will be tested with beam. The other tanks are being pre-assembled for intermediate storage.

12.6 Research & developments of Commons for the FAIR Project

Head: Stefan Menke
Authors: Dr. Ralph Bär, Mario Bevcic, Dr. Frank Hagenbuck, Dr. Holger Kollmus, Dr. Marcus Schwickert, Horst Welker, Dr. Christina Will, Alexander Bergmann, Alexander Etzler

The Subproject Commons takes the responsibility for the following major technical systems (listed .psp numbers according the Work Breakdown Structure (WBS) of FAIR:

- psp 2.3. High Energy Beam Transport (HEB)
- psp 2.14.1 Electric Power (EPS)
- psp 2.14.8 Cryogenics (CRY)
- psp 2.14.10 Controls (ACO)
- psp 2.14.12 Transport and Installation (TRI)
- psp 2.14.xx (smaller work packages, will not be reported in detail)

psp 2.3 High Energy Beam Transport (HEBT)

Authors: Dr. Frank Hagenbuck, Dr. Marcus Schwickert;

Magnets

The series production of batch1 with in total 51 dipole magnets has been in full swing at Efremov Institute of Electrophysical Apparatus in St. Petersburg (Russia) (NIIEFA): Five more of these magnets arrived at GSI in the first quarter of 2020. They were equipped with vacuum chambers and moved to the temporary storage in Weiterstadt, which push the completion of this contract to 84%. To encounter Covid-19 related travel restrictions, GSI initiated and successfully tested a remote FAT procedure with NIIEFA staff. This enables the next shipping of three more magnets to GSI in the beginning of 2021.

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): The first-of-series dip10_0 dipole magnet has been completed and delivered in 2020. In February, six S100 and four S18 steering magnets have already reached GSI. Further ten quadrupole 2 and five quadrupole 11 magnets, that were already reviewed before the pandemic, arrived to GSI over the summer. Also, the usability of a remote FAT program was explored with BINP and seven magnets have passed in 2020. Likewise, 58 of the contracted magnets arrived at GSI by the end of 2020, 20% of the initial contract excluding the ones amended in 2020.

Power Converters

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

Until January 2021, 115 power converters for quadrupole magnets (2 types) and 48 power converters for steerer magnets (1 type) were manufactured, successfully tested and shipped to FAIR.

The finalization of the design of another 44 power converters for quadrupole magnets (5 types) is planned for summer 2021. The series production for 45 power converters for steerer magnets (1 type) is under preparation. The delivery of all these power converters will be completed in the second half of 2022.

Beam Instrumentation (BEA)

Production of detectors and mechanical components continued throughout 2020 at GSI and by our in-kind partners from Slovenia and India. Several deliveries of components from Slovenia were received and passed site-acceptance procedures. The Indian provider Vacuum Techniques Pvt Ltd. completed and commissioned a new and dedicated facility for production and factory testing FAT of 58 diagnostic vacuum chambers. On the whole, progress was regularly monitored in close collaboration between the provider and departments of vacuum VAC and beam instrumentation BEA. With preparations for series production finished and a detailed production plan of three batches in place, a timely supply of components is forecast in 2021 in line with updated project milestones.

In autumn 2020, a Polish partner Co. Prevac joined the project with the aim of delivering 49 SEM-grid detectors for transverse profile measurements and their integration on pneumatic drives. A project team has been established and is currently working on four first of series units to evaluate the production process and assure quality control of the series.

On site at GSI, the beam instrumentation team continued several data acquisition projects, e.g. on current and charge measurements with resonant and fast current transformers, and on beam profile measurements with SEM-grid detectors or Multi-Wire Proportional Chambers. A prototype readout system for beam position monitors, developed in collaboration with the Slovenian partner Cosylab, was completed in December 2020.

Furthermore, Cosylab upgraded the stepper motor control software, driver and FESA class to meet future user requirements for triggered motion control by integration of the FAIR timing receiver board. The final site acceptance test procedure is ongoing. Thereafter, the position readout is intended to be tested with available detectors of the high energy transfer lines with SIS18 beams under realistic operational conditions during the next two years.

Vacuum chambers

In 2020, 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 (NIIEFA). In the meanwhile, 42 chambers were installed into their magnets. Completion of installation of all chambers of batch1 is expected for end of 2021.

3D models and 2D drawings of most dipole chamber types and quadrupole chamber types of the vacuum chambers batch2&3 (BINP) were successfully completed in 2020. The Conceptual Design Review and the Final Design Review for all dipole, quadrupole and steerer chambers will be completed in the second half of 2021. Due to Covid-19 regulations, an alternative remote FAT of three manufactured vacuum chambers for dipole magnets dip13 is planned with the help of TÜV for early 2021.

Lastly, in 2020 first 3D models and 2D drawings for the vacuum chambers of batch4 (BINP), comprising pumping chambers, straight tubes, bellows etc., were received and approved.

Special Stands

Regarding the large support frame in building H0705A, the relevant interfaces between the accelerator components and the building's technical equipment, including installation space for cable routing and media supply, were clarified in 2020. Furthermore, the assembly sequences for the frame and the components as well as the disassembly sequence in the event of maintenance have been coordinated. The Conceptual Design Review is planned for April 2021.

psp 2.14.1 Electric Power (EPS)

Author: Horst Welker

Power Converters

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

Until January 2021, 115 power converters for quadrupoles (2 types) and 48 power converters for steerers (1 type) were manufactured, successfully tested and shipped to FAIR.

The design of another 44 power converters for quadrupoles (5 types) is planned to be completed by summer 2021. The series production of 45 power converters for steerers (1 type) is under preparation. The delivery of all these power converters will be completed in the second half of 2022.

51 power converters for dipole magnets and eight power converters for quadrupole magnets were contracted in the end of 2020. The design of these power converters will be finalized by May 2021 and the series production will start in the second half of 2021. The delivery of the first lot is scheduled for early 2022.

Machine cable management and User Cable

All the user cable data continue to be maintained in the Cable Data Base. Latest update of cable data was provided to Fair Site & Building for the procurement process. A regular communication is established among routing company, FSB and the cable manager. The cable routing process for the first two buildings has started, as well as the planning of the cable trays near the machine.

An Expression of Interest (EOI) was introduced from the Indian in-kind partner for delivery of more cable types.

psp 2.14.8. Cryogenics (CRY)

Author: Dr. Holger Kollmus

The technical department Commons Cryogenics (CRY) is responsible for the GSI and FAIR wide cryogenic helium supply of superconducting magnets and cavities. CRY is presently operating a prototype test facility (PTF), a series test facility (STF), the Helium Supply Unit (HeSu) and two more Cryo plants for R3B GLAD magnet testing and for the cooling of the CRYRING electron cooler solenoid. The main future customers at FAIR are the SIS100 and the Super-FRS with a total helium inventory of about eight tons. Additionally, CRY serves small consumers like the final focusing system of APPA and the large-scale experiments CBM / HADES and Panda.

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

Cryogenic Infrastructure for the Series Test Facility (STF)

The STF has an overall cooling capacity of 1.5 kW @ 4 K equivalent and is equipped with four test benches for magnet testing and one universal connection box. Up to now, the plant has about 50.000 h of operation and more than 100 magnets and 18 SIS100 current lead pairs were tested so far. The first SIS100 Quadrupole modules were tested in 2020, as well as SIS100 local cryogenic modules.

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

For FAIR one central cryo plant will be installed serving the helium cooling capacity for SIS100, Super-FRS, CBM and HADES. It comprises a 19 kW @ 4 K equivalent 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. The final design review (FDR) was accepted in 2020 and the Cryo plant CRYO2, including CWU are in production.

The Cryogenic Distribution System

The Cryogenic Distribution System is divided into three major lots: the SIS100 distribution system, the north/south transfer line including DB2 supplying also CBM / HADES and the Super-FRS distribution system. For the SIS100 distribution system an intense study was already undertaken in 2014. In 2017 and 2018 the pipe routing was finalized with respect to other technical infrastructure installation for the SIS100. After approval of the specification spring 2019 the SIS100 distribution system is in production.

psp 2.14.10 Controls (ACO)

Author: Dr. 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 minor 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).

Since the complete replacement of the old GSI accelerator control system by a basic version of the FAIR control system in the long accelerator shutdown period in 2016-2018, the new system has been successfully operated in two regular beam times in early 2019 and early 2020. This allows to execute a rich experimental physics program with all machines. Over the year 2020, a wide range of improvements on all layers and subsystem components of the control system significantly improved stability and usability of the control system.

After the successful implementation of underlying development frameworks and the implementation of basic operational functionality for synchrotrons, storage rings and beam transport lines, the development focus has been shifted. In 2020, the main effort was concentrated on improving system performance in order to reduce the operational system response and latency time while changes of settings and trims are carried out. This was a well-known inadequacy of the new system, which due to development capacity limitations could not comprehensively addressed before. With cross-system improvement on all layers of the control system, the system performance was substantially enhanced for the upcoming physics beam time 2021 in order to allow an efficient machine setting and trimming by the operation and machine experts team. In parallel, further developments focused on consolidation of the core code base to reduce technical debts for subsequent developments, and on implementation of specific tools and equipment integration for the forefront FAIR machines and their upcoming commissioning phase.

Being still far away from being feature-complete and achieving the specified full performance, a basic version of the FAIR control system is in use and operation already today for the FAIR Phase-0 beam times, 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 on all control system subprojects:

Design and production of the FAIR standard equipment controllers (SCU) for FAIR power converters and many other real-time control systems as well as a variety of corresponding slave boards (ADC, DAC, DIOB, etc.) have been continued. Further 200 units of the first version of SCU are under production now. About 300 SCU units are already installed and operated in the existing machines as part of the accelerator control system upgrade project and many more are ready for distribution to the equipment groups for FAIR system integration. The design of a new revision of the standard controller (SCU4) with an upgraded central FPGA for improved performance is well progressing. Electronics schematics are completed and PCP board design is ongoing. The SCU4 modules will be produced as the second batch of equipment controllers for FAIR.

Significant progress has also been made in 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. All of these systems are already being used in operation. To control the GSI/FAIR complex, new fundamental concepts have been defined and successfully integrated in the LSA core base for physics modelling of the machines and beam lines: Pattern, PBC (beam production chain). All accelerators (CRYRING injector & ring, SIS18, GSI-HEBT and ESR) have successfully been modelled in LSA and have been put to operation.

FESA software development aims to the integration of Libera-based Ring-BPM (beam position monitors), Ring Closed-Orbit-Feedback (COF) System and HEBT-BPM System. In 2020, the equipment control software, respective high-performance data concentrator and post-processor of these systems have been developed by the Slovenian In-kind partner and successfully acceptance-tested. Consequently, these systems are now in standard operation at the existing machines.

psp 2.14.12 Transport and Installation (TRI)

Author: Mario Bevcic

Beside supporting the Accelerator Operation Division in service, reconstruction and upgrade of accelerator components during the shutdown 2020 and for preparing the planned beamtime program, TRI is, together with the Site Management, strongly involved in the development of transportation and installation concepts for the FAIR Accelerator components.

Another aspect in focus is the preassembly of already supplied FAIR Components, especially magnets for HEBT and support of testing and preassembly of SCM Magnets for SIS100.

Engineering, Mechanical Integration: System developed for efficient and transparent data exchange between FSB and GSI

Authors: Alexander Etzler, Alexander Bergmann, Dr. Christina Will

Effective data exchange between FSB as representative for the building construction and GSI as representative for the beamlines is of fundamental importance for the timely and economic success of the FAIR project.

The improvement of process quality is one of possible measures to reduce cost escalations [1]. With the realization of a virtual, daily updated representation of the accelerator facilities in the buildings, a big step towards an efficient collision check between GSI and FSB on the same level of data and information was reached.

In order to create a common representation of buildings and equipment, different data structures have to be merged into one overall system. Beside the large amount of data, also different data formats, different naming systems as well as diverse requirements for this specific information and their representation are challenges to overcome.

For this purpose, a visualization system was developed in 2020, which enables the digital implementation of the procedural requirements placed by an accelerator facility. A quality-assured and up-to-date data exchange between the construction companies and the representative of the beamlines is secured. The results of the various development tools such as CATIA V5® and various Autodesk® applications are merged into a common data format. The representation of the requirements and the results of the different development procedures is visualized in a virtual image. Modifications to the drawings can be automatically integrated and visualized for all stakeholders.

The aim of this system is to perform collision checks between buildings including technical building equipment and accelerator facilities in a quality-assured manner, based on the same database and a uniform level of knowledge, to avoid duplications of work or errors and to ensure a high level of compatibility of the information between the parties involved.

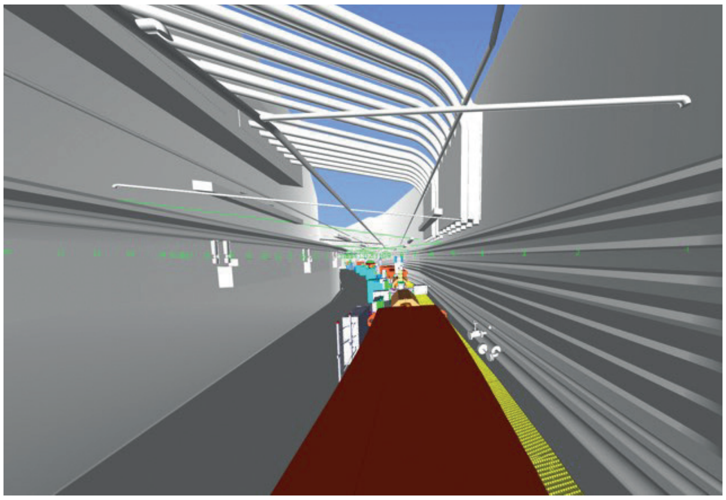


Figure 74. Representation of beam sections in the building with TGA.

Figure 74 shows an example of the result after running through the system, as a virtual image of the building including accelerator in the viewer software Navisworks® Freedom. The models of the buildings and the accelerator facilities are available merged for both FSB and GSI staff members. This allows the monitoring of the target figures in the area of construction.

References

- [1] Spars, G., Obadovic, O. 2021. VDI Wissensforum. Baukostenentwicklung in Deutschland – Treiber und Eindämmungsmaßnahmen. [Online] VDI, 2021. [Zitat vom: 09. 04 2021.] https://www.vdi-wissensforum.de/news/baukostenentwicklung-in-deutschland-treiber-und-eindaemmungsmassnahmen/

13. Executive summary of the accelerator operations and operation of infrastructure support

Head: Mei Bai, GSI
Authors: M. Bai, G. Franchetti

During the past half year, the Accelerator Operations Business Area (ACC) successfully carried out the second Physics Run in the first and second quarter of 2020 and has been currently carrying out shutdown activities in preparation for the beam time 2021. In addition, the GSI ACC operations continued its effort in contributing to the various FAIR project work packages as well as leading the update of existing facilities.

Despite the unexpected pandemic COVID-19 outbreak, the 2nd Physics Run reached the following achievements, many thanks to the efforts and collaborations over the campus,

- About two thirds of the scheduled experiments were carried out. Due to the COVID-19 related travel restrictions, about 30% of the experiments had to be postponed beyond this operation period.
- ESR successfully delivered the required beams for its users, including for the very challenging beta decay experiment on bound state beta decay, which user suppered by an ERC grant.
- Successfully commissioned the CRYRING with the beams from the ESR. Pb beam from the ESR was not only injected, cooled and stored in the CRYRING, but also further decelerated in the CRYRING to 4MeV/u.
- A dedicated machine development in re-establishing high intensity heavy ion beam through GSI accelerator complex was successfully carried out. Due to the safety restrictions w.r.t. COVID-19, this campaign was completed with Bismuth beam instead of uranium beam as originally planned. With the joint effort of UNILAC operations team and SIS18 operations team 3e10 Bi^{28+} was established in the SIS18, a major step towards FAIR goals. This was only possible with the pulsed H2 gas stripper and the stable performance of UNILAC HSI RFQ together with excellent optimization through UNILAC. The beam performance through out UNILAC was carefully evaluated and corresponding upgrade measures are proposed and will be planned accordingly.

In addition to the operation of GSI existing facilities, ACC continued its commitments to the FAIR-Project in leading the work packages of p-Linac proton source, p-Linac RF, dedicated uranium injector as well as the stochastic cooling for the Collector Ring (CR). The operation infrastructure support of ACC, i.e. the galvanic workshop and the mechanic workshop as well as the Technology Lab also continues its strong technical support across the campus. At the same time, the newly developed integrated planning of copper plating p-Linac and new Alvarez post stripper of UNILAC has been on good track in conjunction with the planned galvanic workshop refurbishment project. In particular, the galvanic workshop has finally successfully copper plated the demonstator of the FOS tank.

Besides the technical and R&D activities, the GSI ACC has been progressing well in the UNILAC post stripper upgrade project. The dedicated post striper upgrade team has been fully focusing on the completion of the FOS project so that the series production can take place as soon as possible.

The ongoing COVID-19 pandemic crisis continues to post a lot of challenges in various activities. Nevertheless, a set of actions under the guideline of GSI/FAIR Task Force Health has been taken to ensure the ongoing shutdown work for the upcoming beam time, upgrades and improvements of existing facilities as well as FAIR project work packages. These measures include home-office, flexible work organization, re-enforcing safe distance, providing disinfection solution, masks etc. to ensure the safe working awareness.

Details of these activities are reported in the following chapters.

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13.1 User Beam Time Report

13.1.1 General report of the user beam time

Authors: S. Reimann, O. Geithner, M. Klich

In January, the re-commissioning of the complete accelerator complex at GSI including Cryring@ ESR was started for the 2nd beam time of FAIR Phase-0. From February 10th to June 7th, beam was continuously provided for the planned experiment and machine physics program. An originally planned maintenance break was cancelled in April due to lack of demand, with the result of extending the effective beam time for experiments. Also in April, it became apparent that the effects of the Covid19 pandemic would also affect accelerator operation. In close coordination with the Task Force Health, a concept was then developed to ensure that operations could be maintained at nearly full capacity. The control room was closed to visitors and access was generally severely restricted. The usual distance regulations were enforced in the control room and disinfectants and masks were provided.

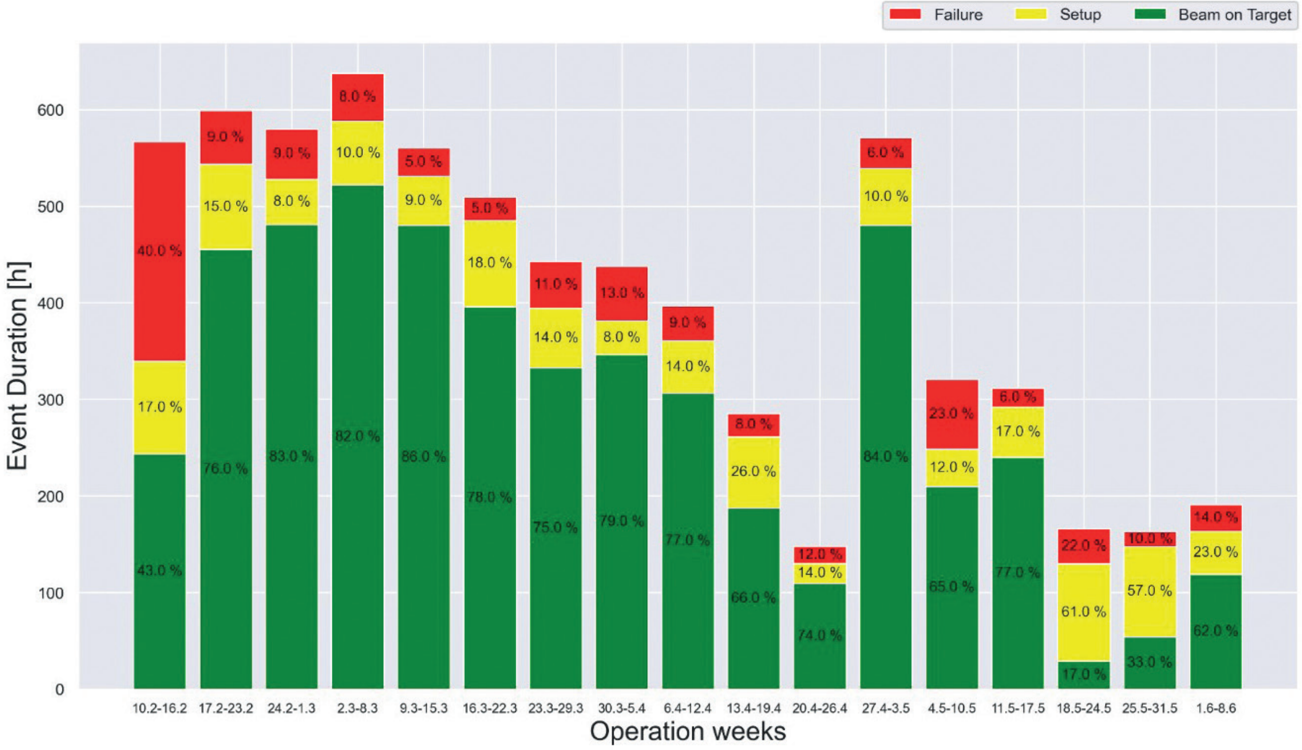


Figure 75. Weekly accelerator performance. The bars represent the integral beam time of one week over all experiments running in parallel. After the usual start-up difficulties, the accelerators ran with high availability, but with a decreasing experimental program. Therefore, a parallel machine run for engineering and machine experiments was started at the end of April. On May 4, the experiment program was terminated early due to Corona travel restrictions. In the final three weeks, the campaigns for bismuth and proton operation were carried out. This period is therefore dominated by setup time.

Unfortunately, due to travel restrictions, in May several cancellations of experiments by the experiment collaborations followed. Some major experiments could therefore no longer be performed. However, as the new operating mode could be established very well, it was decided to keep the operation running anyway and to relax the beam time schedule. The remaining experiments could be given more time and the time becoming free was used for the recommissioning of complex operating modes at the ESR and Cryring with the new control system. In addition, a campaign with high-energy protons and a high-current campaign with a high-intensity bismuth beam was successfully carried out. In this way, the beam time was used effectively and completed as planned with high availability (Figure 75).

Subsequently, a dry run was carried out to test new control system developments, including measurements on the performance of the data supply. During the beam time, it became obvious that a large gain in efficiency can be expected through an improvement of trim latency.

Ion statistics

During the beam time, 13 different ion species from 4 different source types were accelerated (Table 2). The longest run times were lead with 1036 hours and calcium with 1682 hours. From the CH_3 molecule proton and carbon beam was produced from one ion source. The molecule split was done in the UNILAC gas stripper.

Source	mass	element	charge	duration / h
UNILAC ECR	2	H_2	1	138
UNILAC ECR	4	He	1	86
UNILAC ECR	12	C	2	152
UNILAC MUCIS	15	CH_3	1	529
UNILAC PIG	40	Ar	1	169
UNILAC ECR	48	Ca	10	1682
UNILAC PIG	50	Ti	2	577
UNILAC PIG	56	Fe	3	158
UNILAC MUCIS	86	Kr	2	162
UNILAC MUCIS	124	Xe	3	623
UNILAC PIG	197	AU	8	398
UNILAC VARIS	206	Pb	4	1036
UNILAC VARIS	209	Bi	4	557

Table 2. List of accelerated ion species. From the CH_3 molecule, proton and carbon beam were produced in the stripper.

Failure statistics

In the beginning of beam time the Availability Working Group (AWG) was established to consolidate the quality of the failure data from the logbook. Maintained Failure Data have now more acceptance in the expert groups and could be a reliable basis for financial decisions by the management.

The failures are classified in distinct main categories and the following table shows the failures with the longest downtimes.

Main category	Duration of failures in h	Number of failures
Electric Power Systems	146,22	146
Controls	119,74	70
Infrastructure	96,54	31
Miscellaneous/Unknown	80,12	46
LINAC	63,43	204
Vacuum	39,92	23
LINAC RF	39,76	132
Injection/Extraction	39,08	33
ZKS	19,43	2
Vacuum Leak	16,55	21

Table 3. Duration and number of failures during beam time divided in different categories.

For example the downtime caused by the electric power systems increased proportional to the duration of the beam time. The main reasons for the downtime were long failures overnight: the power converter for HFSMU1 had to be rebuilt, the power converters for the SIS18 corrector had problems with ramping and some failure were often reset without an information to the expert group.

The failures in the main category "LINAC" were caused by a vacuum leak in the HLI RFQ, frequent vacuum spikes in the device GUS4BB3 and GUS4BB4 and defective coil in the device GUT2MUZ.

13.1.2 Ion sources operation report

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

The ion sources department provided in 2020 various types of ion species for a user beam time as well as for an engineering run. The high current ion sources (Multi Cusp Ion Source MUCIS and Vacuum Arc Ion Source VARIS) from Terminal North, the Penning ion sources (PIG) from Terminal South and the ECR Ion Source (ECRIS) from the High Charge State injector HLI were supplying the GSI-UNILAC in parallel operation. The following table shows the ion species delivered to the accelerator. Representative values of intensities are the analysed beam currents in front of the High Current Injector (HSI)-RFQ and of the HLI-RFQ, respectively.

Ion species	Duty Cycle*	Intensity (RFQ/emA)	Ion source	Duration (days)
Physics run (February-May)				
$^{4}He^{+}$	cw	0.4	ECRIS	5
$^{12}C^{2+}$	cw	0.08	ECRIS	7
$^{48}Ca^{10+}$	cw	0.09	ECRIS	65
$^{15}CH_3^{1+}$	2Hz/0.5ms	2	MUCIS	14
$^{86}Kr^{2+}$	1Hz/1ms	5.6	MUCIS	7
$^{124}Xe^{3+}$	1Hz/1ms	3.3	MUCIS	27
$^{206}Pb^{4+}$	1Hz/0.35ms	3	VARIS	15
$^{208}Pb^{4+}$	1Hz/0.4ms	6	VARIS	29
$^{209}Bi^{4+}$	1Hz/0.4ms	6	VARIS	15
$^{40}Ar^{1+}$	5Hz/1.5ms	0.8	PIG	5
$^{50}Ti^{2+}$	50Hz/5ms	0.05	PIG	8
$^{197}Au^{8+}$	25Hz/5ms	0.04	PIG	20
$^{56}Fe^{3+}$	5Hz/1ms	0.12	PIG	6
Engineering run				
$^{40}Ar^{8+}$	cw	0.16	ECRIS	10
$^{1}H_2^{+}$	cw	0.17	ECRIS	7
$^{209}Bi^{4+}$	1Hz/0.4ms	6	VARIS	8
$^{15}CH_3^{1+}$	2Hz/0.5ms	2	MUCIS	11
$^{50}Ti^{2+}$	25Hz/1ms	0.05	PIG	6

Table 5. 2020 beamtime in ion species, duty cycle, intensity, ion sources and duration in days.

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

The ECRIS at the HLI was in operation for the engineering run to provide $^{40}Ar^{8+}$ and $^{1}H_2^{+}$. Concerning the physics runs, $^{4}He^{+}$ and $^{12}C^{2+}$ were requested for biophysics experiments, while $^{48}Ca^{10+}$ was used for the Super Heavy Element (SHE) and Material Research programme. A higher $^{48}Ca^{10+}$ intensity has been achieved with a tungsten grid mounted in the oven head used for the evaporation of metal elements and compounds. Furthermore, a diagnostic set-up based on an Optical Emission Spectrometer has been successfully installed at HLI to improve the ion beam stability.

The Penning ion source was in operation for physics runs to provide $^{197}Au^{8+}$ beam for the material research program and plasma and biophysics experiments, $^{50}Ti^{2+}$ for direct mass measurements at SHIPTRAP and for chemical studies, besides $^{56}Fe^{3+}$ beam for biophysics experiments and materials research. For the engineering run a $^{50}Ti^{2+}$ beam has been used for operator training.

For the physics run the high current ion sources from Terminal North were in operation with the following ion species: MUCIS was providing high intense Methane beam for the production of protons and Carbon ions (simultaneously behind the gas stripper) for HAD, HTM and HFS. The MUCIS delivered $^{86}Kr^{2+}$ beam for HFS-HTC and ESR and $^{124}Xe^{3+}$ beam for FRS and ESR. The VARIS was providing highly enriched 206-Pb and 208-Pb beam for the very first time for HFS, HTP, HTD and ESR. The one month beam time was surprisingly running very smoothly without any single ion source exchange. No other element from VARIS runs as easy and smooth. The VARIS was also providing high intense Bismuth beam. The listed duty cycle, especially for the VARIS is the maximum value, using e.g. for the setup time. When the experiment is running, the ion source operates in request mode, at an often five times less duty cycle. This explains the relative long lifetime of the ion source.

13.1.3 UNILAC Status Report

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

Operation and related works

In 2020 the UNILAC was in operation for 101 days of user beam time (10th February to 20th May 2020), for 19 days of the "Beam Parameter Campaign" with bismuth (20th to 28th May) and for machine experiments with proton beam (28th May to 8th June), despite the Corona crisis with its restrictions since 15th March 2020. Additionally, UNILAC delivered argon beam for 12 days from all three ion sources (16th to 27th November) during the engineering run. Before the user beam time started, extensive RF conditioning (13th to 26th January), Dry run (27th January to 2nd February) and recommissioning/beam setup phases (3rd to 9th February) took place.

The beamtime was dominated by the successful delivery of high intensity ^{208}Pb and ^{209}Bi (VARIS) beams for the synchrotron, and high duty cycle ^{197}Au (PIG) and ^{48}Ca (ECR) beams for the experiments at the UNILAC. After a planned break of the ECR ion source operation, due to construction works in the HLI hall (5th to 11th May), the ECR was re-started for the very first time successfully with the same oven that had already been used (calcium filling). Unfortunately, a failure of the RF coupling loop at HLI IH cavity occurring four days later made it impossible to provide Calcium beam for the experiments for a longer time. Besides for user experiments the bismuth beam has been also exploited for the beam study campaign. In this frame, high current bismuth beams, also using the gas stripper in pulsed operation with hydrogen gas, were optimized at UNILAC and SIS, to provide for reliable beam intensity values that can be offered for future routine user operation.

During the carbon beam operation in February, a horizontal jumping of the beam spot at the end of the transfer channel (up to 10 mm at vacuum section TK7) disturbed beam operation. After many attempts to find out the reason, a slight jumping of the coil current of the strongest TK dipole magnet was identified as being responsible (0.2%, set value 130 A): After changing the power supply from field control to current control the effect disappeared. Later it could be found out that the hall probe's amplifier box was not sufficiently insulated against ground.

Besides the above mentioned ion species, the ECR delivered H_2^+-ions for tests, and $^{4}He^{1+}$ and $^{12}C^{2+}$ for user operation. The PIG ion source delivered Ar^{1+} for commissioning, $^{50}Ti^{2+}$ for user operation and again later for operator training, and $^{56}Fe^{3+}$ for user operation. The MUCIS ion source delivered the protons from CH_3^+ also for user operation, as well as $^{86}Kr^{2+}$ and $^{124}Xe^{3+}$. The VARIS ion source also provided ^{206}Pb beam for user operation. Due to the corona crisis no Uranium beam time was scheduled.

Shutdown 2020 activities

As the very first work in January 2020, a leakage at the stem water connector of Alvarez A1 drift tube no. 14 was repaired, and a broken phase probe in vacuum section UH4 has been finally re-installed.

During the beamtime (until June) and also during shutdown (until December) some water leakages occurred and had to be repaired. The listing comprises the first quadrupole triplet in the HSI IH1 tank (re-brazing of coil tubes), the RF feed loop of the HLI IH tank, the plunger of the 108 MHz-TK rebuncher BB11 and its RF coupling loop (water loss into RF feed waveguide), the Alvarez A3 drift tube no. 8 (manufactured in house at GSI mechanical workshop), the Alvarez A2 drift tube no. 75, the septum coil UT2MUZ (leakage 31st March) and at least two water leakages at Z-branch components (UZA and UZE in the UNILAC experimental hall).

A ground fault of a HSI steerer magnet could be repaired in house by the TRI-department.

ATEX rough pumps were installed at the UNILAC main roots pump, placed at the stripper section.

Three defect vacuum section valves were replaced and the pre pump oil was exchanged.

The transmitter control of the Alvarez A1 amplifier was modernized, the new Alvarez A4 amplifier final stage was checked with respect to EMC (electromagnetic compatibility).

The control software of the timing unit was modified for reliable10 Hz operation of the upgraded Alvarez A4 amplifier.

A new radiation protection door at the beam separation section of UNILAC experimental hall was installed.

The power supplies for eight dc steerer magnets in the HSI Low Energy Beam Transport section were replaced.

A major part of the UNILAC vacuum controls upgrade was finished, after some residual work in the Material Research-Branch.

13.1.4 SIS18 Operations

Author: J. Stadlmann

SIS18 was operated in one Beam Time Block in 2020. Due to the corona pandemic situation an adopted user beam-time was conducted and an engineering run directly after the regular beam-time.

The beam-time was hampered by polluted rain water leaking into the electric power supply of the complete supply room of the SIS18 kicker system and electrostatic septa. The electric power supply had to be powered down for that room. The power supply of the septa was rearranged to another outlet for operation of the slow extraction system. The magnetic kicker system was kept inoperative preventing the use of fast extracted beam.

Overall SIS18 was operated to nominal performance. Setup times were considerably longer due to long “trim times” with the newly developed control system. A dedicated task force performance was formed after the beam-time and could improve this situation considerably till the restart of accelerator operation in 2021.

The engineering run included test operation with Protons. The feasibility of SIS18 to provide slowly extracted Proton beam at a rigidity of 18 Tm (4.5 GeV/u Proton energy) could be reestablished for the first time since 20 years. Slowly extracted Protons of above 4 GeV/u energy are a requirement of proposed and approved experiments in 2021 and beyond.

13.1.5 HEST Report

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

In 2020 the high-energy transfer lines (HEST) at GSI delivered routinely beam to many different users such as caves C, D and M. Immediately after the first beam was sent from ESR to CRYRING with the new control system during the engineering run 2019 [1], ion beam has been delivered again to CRYRING for further commissioning and more intensive beam studies. However, the beam line set-up for low energy was very difficult and resulted in a non-optimal transmission. As a conclusion, the beam instrumentation in this transfer line has been upgraded with three new Faraday cups during shutdown 2020, in order to improve the beam losses localization. Further investigations are ongoing.

In addition to the beam delivery to CRYRING, beam from the ESR extracted by charge exchange extraction was transported towards cave A for the first time utilizing the new control system. The beam had to be stopped in front of the cave at a fluorescent screen since cave A was not ready to take beam due to the given pandemic conditions. However, a machine study on ion optics and emittance measurements could be performed.

For future experiments at cave M, requiring radioactive beams, the new beam path via the fragment separator (FRS) is necessary, which has never been used so far. In order to prepare this transfer line, new beam optics set-ups have been elaborated by the FRS team and the control system has been adapted. The first beam at cave M using this path is expected at beamtime 2021.

Since 2020, the new online model application “Benno”, which is currently under development, is used regularly by the operators. It displays the beam envelope derived from the actual accelerator-magnet settings, allows to change the envelope and the trajectory by mouse click and to send the changed settings to the machine. Technically it is based on the MAD-X beam dynamics simulation code from CERN with which it communicates via the JMad Java programming interface. MAD-X is also used as a general simulation tool for the HEST, and therefore there is a strong need for improved beam optics models of the HEST transfer lines for MAD-X. Significant efforts have been made to generate MAD-X optics models, which are in good agreement with the well-established optics models applying the MIRKO simulation code. For this purpose a Python script has been developed, which generates automatically all required MAD-X input files from a MIRKO-MIX-file and a MIRKO-generated Twiss-file. As an example, a comparison of the MIRKO and MAD-X optics for a HEST transfer line is shown in Figure 76.

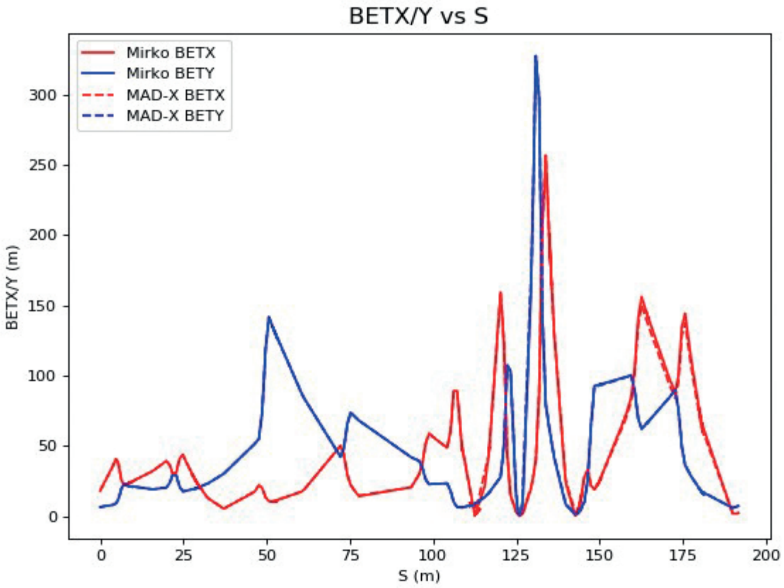


Figure 76. Comparison of the beta functions along the transfer line from SIS18 to the experimental station “HTP” computed with the MIRKO and the MAD-X generated models.

Furthermore, substantial work on the MIRKO optics itself has been performed: The so-called legacy optics [1], which are optics based on magnet settings of the former control system, have been verified and updated wherever necessary with existing validated settings.

References

- [1] Hessler, C. and Sapinski M.: HEST setting management and Engineering Run 2019, GSI-FAIR Scientific Report 2019, GSI-2020-00416, p.119 (2019)

13.1.6 ESR Status

Author: M. Steck

During the beam time period 2020 the recommissioning of the ESR with the new control system was continued. The main focus was the implementation of the storage ring mode which remediates the limitation of the cycle length and thus allows beam storage for extended time periods. Compared to the previous synchrotron mode which limited the time of beam storage to about 20 seconds, stable beam storage was demonstrated for several hours. The storage time can be extended to any required duration, virtually without any limitation. All recommissioning work and operation for physics experiments was performed using the storage ring mode. This mode is matched to the requirements of storage ring operation. It allows to control and vary ring parameters while the beam is stored, particularly required to optimize the beam storage and cooling according to the requirements of experiments when experimental conditions are already established. It also allows adjustment of the duration of beam storage when the beam is already circulating.

The recommissioning included various aspects of operation. After establishing the beam transport of secondary beam from the fragment separator FRS, cooling assisted beam accumulation of secondary beams was implemented. Beam deceleration was performed and optimized with particular focus on the preparation of decelerated beams for fast extraction and transport to CRYRING and in the coming years to HITRAP. These efforts resulted in the first successful transfer of a decelerated beam from the ESR and the storage of highly charged ions in CRYRING. An important activity was the improvement of the ion optical model which is used in the new control system to operate the ESR. Extensive tune and chromaticity measurements were performed and analysed which will enter into the control of magnetic components of the ESR. There are also efforts to develop tools to study the machine parameters by advanced computer simulations.

The control of cooling devices in the course of the deceleration process is an indispensable prerequisite for efficient deceleration and was another activity during recommissioning. Both for electron and stochastic cooling the control of devices can now be performed in the frame of the new control system. The cooling systems require operation modes which are not fully consistent with the general concept of ramped devices of the ring and which allow the tuning of the cooling system when the beam is stored.

The optimization of the ESR operation was supported by various new diagnostics tools which allow the measurement of orbit and tune, both during storage and deceleration. This information was used to refine the ion optical model which has undergone various changes during the transition from the old to the new control system. First tests of precise orbit and dispersion control were successfully performed, but will require further development time before they can be available routinely in user operation.

The recently installed barrier bucket rf system has been tested and optimized in beam experiments. The integration of this system into the control system and the machine operation in view of the coming machine operation has been continued. As a first step it will allow the generation of a single bunch for the more efficient transfer of decelerated beam to CRYRING. In the next step this system will be employed in beam accumulation of secondary beams. This will be possible as soon as the low level rf system is prepared for the operation of the ESR barrier bucket rf system synchronized with the SIS18 rf systems.

The ESR was providing beam to various FAIR Phase-0 experiments. One important mode is deceleration of highly charged ions. The decelerated ions were used in experiments employing the internal gas jet target with energies down to 10 MeV/u. Lower energies were initially not available, but after an upgrade of the control system the full design energy range down to 3 MeV/u is now supported. Large interest for the coming years is the deceleration of highly charged heavy ion or rare isotope beams and subsequent transfer to CRYRING or HITRAP using fast extraction. The feasibility of the transfer of decelerated ions was demonstrated, but more machine development will be needed to optimize the deceleration with respect to efficient deceleration and short cycle times. This is impeded by fact that the magnetic cycle and cooling scenario depends on the required ion species and energy after deceleration.

To provide increased intensities of secondary beams, special accumulation procedures were developed in the past. The method of accumulation was implemented into the new control system and demonstrated in an experiment which aimed at storage of an intense secondary beam. The accumulation in the longitudinal phase space used the combination of stochastic cooling of the injected beam on an outer orbit, the deceleration with the rf system to an inner orbit and the continuous electron cooling of the accumulated stack on the inner orbit. This was used in an experiment which also demonstrated the storage of a high energy beam which has the necessary lifetime for extended periods up to 10 hours.

Another method which was used in an experiment was the detection of electrons which emerge from interaction of a decelerated ion beam with the internal gas target and the energy separation of the electrons in a magnetic spectrometer installed behind the internal gas target. The operation of the electron spectrometer was integrated into the ring control.

The operation of the ESR with low energy beams and the measurement of beam lifetimes revealed that the average vacuum pressure in the ESR is about 1×10^{-10} mbar. As this will limit the performance for the lowest energies, replacement of outdated vacuum components is foreseen in the coming years.

13.2 Shut-down activities

13.2.1 General shut-down activities

Authors: P. Schütt, M. Vossberg, M. Klich

In June 2020, all accelerator facilities were shut down for maintenance. Apart from short device tests and dry runs, they went back into operation in February 2021 as scheduled. Maintenance and repair work in 2020 could be performed as planned without major restrictions due to the Covid19 pandemic.

Here, we give a general overview of the major shut-down activities. Not mentioned are regular periodic maintenance tasks and minor repairs of failures that had occurred during beam time.

Planned Activities in 2020

Construction work on buildings, cranes etc.

During planning activities for the refurbishment of the large crane in EX hall, major faults in the crane rails were detected. Thus, the refurbishment was postponed and the rails were repaired. The roofs of halls EX and TR were renovated to tighten them against rainwater. In order to improve fire protection in the halls TR, EX and TH, escape routes were marked, new stairs were installed and the extinguishing areas in the SIS18 tunnel were clearly marked.

The construction of tunnel 101, the connecting tunnel between SIS18 and SIS100, also required a time slot without beam time. During the shut-down, the earthwork which shields the construction area from radiation was removed to install part of the tunnel, and reinstalled by the end of the year. Survey and alignment of the SIS18 and connected beam lines was shifted to January 2021 to include changes of vertical position, which are caused by the FAIR construction work.

The refurbishment of fire protection and technical building installation in BR3 had a major impact on the usability of the main control room. Up to now, access requires passing the construction area. However, work inside of the control room was finished in time to enable operation for the beam time 2021.

Accelerator Control system

The focus of the development of the accelerator control system in this shut-down period was on consolidation and code restructuring. The main result for operation was a significant improvement of the performance during tuning [H. Hüther, GSI Report 2020].

UNILAC

At UNILAC, we faced many issues due to aging structures: several cooling water leaks needed fixing, e.g. a drift tube of Alvarez tank A3 was exchanged. Vacuum leaks and electric short cuts caused major repair work in the tunnel septum and a low energy steerer. Roots pumps in the stripper section were replaced.

The Linac RF department prepared and successfully performed the official EMC (electromagnetic compatibility) acceptance test for the new Alvarez A4 sender and refurbished the Alvarez A1. The new A4 sender requires special treatment in the control system in order to enforce the limits of 10 Hz and 1 ms pulsed operation. Many side effects of this change needed follow up during and after this shut-down.

The main challenge in these tasks was the conflict between boundary conditions needed for repair (tunnel access) and for RF conditioning and tests (tunnel closed). [U. Scheeler, GSI Report 2020]

SIS18

The new IPM (ionization profile monitor) was installed in the SIS18 ring. The bunch compressor cavity was re-commissioned after reinstallation of the electronics, which had been used for tests of the SIS100 systems.

The new cavity for spill smoothing was prepared and tested for installation. Due to unexpected heating of RF ceramics (inconsistence with data sheet), the installation could not be conducted in 2020.

ESR

The main open task at ESR is the repair of a short cut inside the electron cooler. This was postponed to a later longer shut-down period. Thus, in 2020, the focus was on preparation of experiments planned for 2021 and an update of controls of the main dipole and quadrupole power supplies.

Cryring@ESR

A new ion source was installed including a new low energy beam line. Inside the ring, a prototype for the CCC (cryogenic current converter) was installed for test with beam. Experiment installations for the upcoming beam time were done.

Unexpected Issues

In February 2020, during beam time, the power distribution (IB01) in the SIS18 Kicker Room switched off due to a short-cut caused by intruding liquid. While this problem could be temporarily solved to continue beam time, it enforced major repair work and thus delayed the maintenance work on the SIS18 injection and extraction devices. The power distribution was handed over for operation on October 21st.

An accident in the LBH hall caused major delay in shutdown work: a beryllium vacuum window broke and the decontamination turned out to be difficult and time consuming. For eight weeks, no work was possible at the vacuum test bench. Spare parts and tools were inaccessible for several other departments, too.

Outlook for 2021

Before the beam time 2021, the beam diagnostics department managed to install three new Faraday cups in the beam line between ESR and Cryring@ESR.

Afterwards, in February 2021, the beam time started successfully.

13.2.2 Task Force Performance Project Report

Authors: H. Hüther, J. Fitzek, O. Geithner, F. Herfurth, C. Hessler, S. Litvinov, B. Lorentz, S. Krepp, R. Müller, Dr. D. Ondreka, A. Schaller, J. Stadlmann, R. Steinhagen, M. Steck, A. Walter

Background

After several years of focusing on new features and enhanced reliability, priorities for control system development at GSI-FAIR were adjusted towards performance improvements in 2020. During the Technical Integration Meeting in March, the importance of such an effort was underlined and the request made to establish a task force to carry out its implementation.

Task Force Members, Responsibilities and Objectives

The Task Force Performance consisted of controls, machine and operations experts. Duties of non-ACO members included decision making and prioritization as well as providing use cases, leading to strong stakeholder involvement. The following is a shortened version of the task force's objectives, which were phrased and agreed upon during the kick-off meeting:

Primary objective

Achieve substantially improved performance for currently most relevant use cases, so the facility can be operated efficiently

Secondary objective

Check for potential performance issues that may become relevant for FAIR (i.e. SIS100 and beyond)

Scenario-based Approach

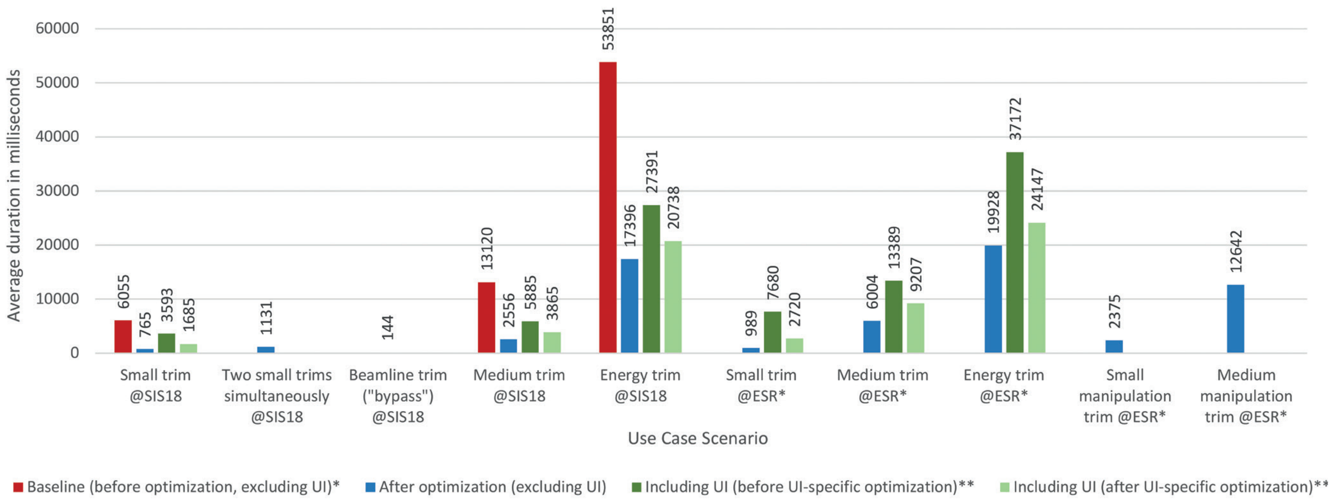
Instead of optimizing performance from a system-centric point of view, the task force took the operator's perspective, asking the question "For which use cases must performance be improved?". Use case scenarios were established to make requirements concrete and specific. Measuring these scenarios allowed for quantifying the status quo and subsequent improvements. That way, progress was made traceable and verifiable.

To serve as a starting point for analyzing performance bottlenecks and to have a baseline to compare improvements against, an initial set of measurements were performed. These measurement results served as a basis to achieve a common understanding of performance deficits within the process of changing setting values (usually called "trim"). Task force members agreed on a "top time wasters" strategy, meaning that implementers would go for optimizations with (relatively) low effort and high expected impact.

Implementation and Results

Following the aforementioned approach, an end-to-end view on the trim process was taken, leading to optimization measures being implemented throughout the control system stack.

For the scenarios that were optimized, which are considered to cover the most important day-to-day operating use cases, wait times have been significantly reduced. For example, as shown in Figure 77, processing time for a "small trim" scenario affecting a single magnet at SIS18 has been reduced by 87% from the baseline of 6.055 to 0.765 seconds. On the other end of the complexity spectrum, processing time for an “energy trim” affecting roughly 150 devices has been reduced by 68% from 53.851 to 17.396 seconds. Note that these numbers do not include UI processing time as that has been optimized separately (as indicated by the green bars in the diagram).



* Baseline measurements are available for "small" / "medium" / "energy trim" scenarios at SIS18 only.

** Data including UI (ParamModi) processing time (green bars) is available for "small" / "medium" / "energy trim" scenarios at SIS18 and ESR only. Measurements have been performed during the November 2020 dry run, so both "before" and "after UI-specific optimization" refer to the "after optimization" state (blue bars) of underlying systems.

Figure 77. Measurement results by Use Case Scenario.

Since other control system developments took place at the same time, measurement runs performed at different points in time might not be fully comparable. When interpreting the numbers, keep in mind that also changes in system environments, measurement methods and external factors affect measurement results. Consequently, they should only be considered a rough indicator of to-be-expected performance.

Although there are no baseline measurements available for ESR scenarios, as these were introduced at a later stage of the project, after-optimization results and spot checks indicate that ESR has benefitted to a comparable extent.

In addition to generic speedup measures, specific new features were introduced to further reduce wait times in especially affected scenarios such as simultaneous trims at independent machines (such as SIS18 and ESR), beamline optimizations and trims made by beam-based feedback systems.

Summary

To the extent that results can be assessed through measurements, all primary and secondary objectives are considered fulfilled. No fundamental technical issues or architectural problems were encountered during the project.

As always, operation during the beamtime should be considered the final test, but feedback received so far suggests that the measures implemented actually translate to perceivable improvement for operators, machine modelers and developers.

Outlook

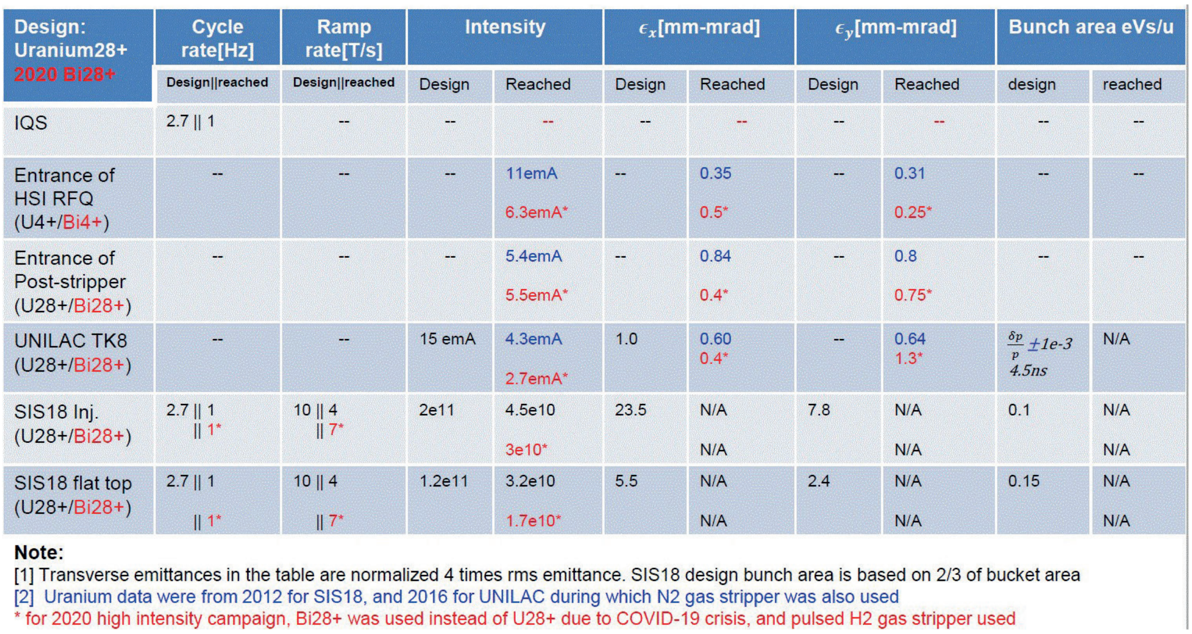
Measurement snapshots capturing data from actual operation will be taken during the 2021 beamtime. Analysis will be performed on a best-effort basis and discussed during a follow-up meeting.

Although the task force’s project is considered successfully completed, maintaining performance will be an ongoing activity: Introducing new features as well as incorporating additional machines to the control system will bring new challenges in that regard. Nevertheless, both experience gained in Controls and other departments as well as performance measurement mechanisms established will prove beneficial to overcome these challenges.

13.3 Beam Parameter Study Campaign

13.3.1 Introduction of the campaign

Author: B. Lorentz



Design: Uranium28+ 2020 Bi28+	Cycle rate[Hz]	Ramp rate[T/s]	Intensity		ϵ_x[mm-mrad]		ϵ_y[mm-mrad]		Bunch area eVs/u	
	Design||reached	Design||reached	Design	Reached	Design	Reached	Design	Reached	design	reached
IQS	2.7 || 1	--	--	--	--	--	--	--	--	--
Entrance of HSI RFQ (U4+/Bi4+)	--	--	--	11emA 6.3emA*	--	0.35 0.5*	--	0.31 0.25*	--	--
Entrance of Post-stripper (U28+/Bi28+)	--	--	--	5.4emA 5.5emA*	--	0.84 0.4*	--	0.8 0.75*	--	--
UNILAC TK8 (U28+/Bi28+)	--	--	15 emA	4.3emA 2.7emA*	1.0	0.60 0.4*	--	0.64 1.3*	$\frac{\delta p}{p}$ ±1e-3 4.5ns	N/A
SIS18 Inj. (U28+/Bi28+)	2.7 || 1 || 1*	10 || 4 || 7*	2e11	4.5e10 3e10*	23.5	N/A N/A	7.8	N/A N/A	0.1	N/A N/A
SIS18 flat top (U28+/Bi28+)	2.7 || 1 || 1*	10 || 4 || 7*	1.2e11	3.2e10 1.7e10*	5.5	N/A N/A	2.4	N/A N/A	0.15	N/A N/A

Note:
[1] Transverse emittances in the table are normalized 4 times rms emittance. SIS18 design bunch area is based on 2/3 of bucket area
[2] Uranium data were from 2012 for SIS18, and 2016 for UNILAC during which N2 gas stripper was also used
* for 2020 high intensity campaign, Bi28+ was used instead of U28+ due to COVID-19 crisis, and pulsed H2 gas stripper used

Figure 78. Overview of the U^{28+} beam qualities at various places in the accelerator SIS18.

Future FAIR operation requires the GSI accelerator chain to deliver much higher intensity then it has achieved so far. This is in particular challenging for the low charged uranium beam, i.e. $^{238}U^{28+}$, due to the dynamics vacuum instability in the SIS18. The design of SIS100 requires 5e12 protons and 1.2e11 $^{238}U^{28+}$ per SIS18 cycle respectively.

In order to achieve this goal, there has been a series of measures ranging from UNILAC upgrades to SIS18 upgrades to address the dynamics vacuum instability as well as increase the ramp rate. In addition, high intensity campaigns in UNILAC and SIS18 were carried out starting 2010. In 2012, SIS18 reached 4e10 U^{28+} at 200 MeV/u, a world record.

After the long shutdown from 2016 to 2018, in 2020 a dedicated high intensity campaign was carried out. During 2020 the applicable voltage to the HSI-RFQ has been considerably below the required level for uranium (an issue being resolved in the meantime). Therefore, the campaign was executed with Bi^{28+} instead of U^{28+}.The one-week campaign was carried out with integrated development planning of the full complex, in particular UNILAC and SIS18.

Many thanks to the joint effort from all teams including the experts in setting up the pulsed gas stripper for UNILAC campaign, it was possible to re-establish the performance around 2012 through the future FAIR injector, i.e. UNILAC and SIS18. The following table summarizes the currently best achieved performance together with the design parameters. Detailed reports from each accelerator for the campaign are presented in the following sections, respectively.

As part of the roadmap of GSI facility towards FAIR, this campaign is planned to repeat during each beam time block.

13.3.2 UNILAC Beam Parameter Study Campaign

Authors: W. Barth, A. Adonin, R. Hollinger, U. Scheeler, H. Vormann, S. Yaramyshev

Pulsed hydrogen gas stripper for high intensity heavy ion beams

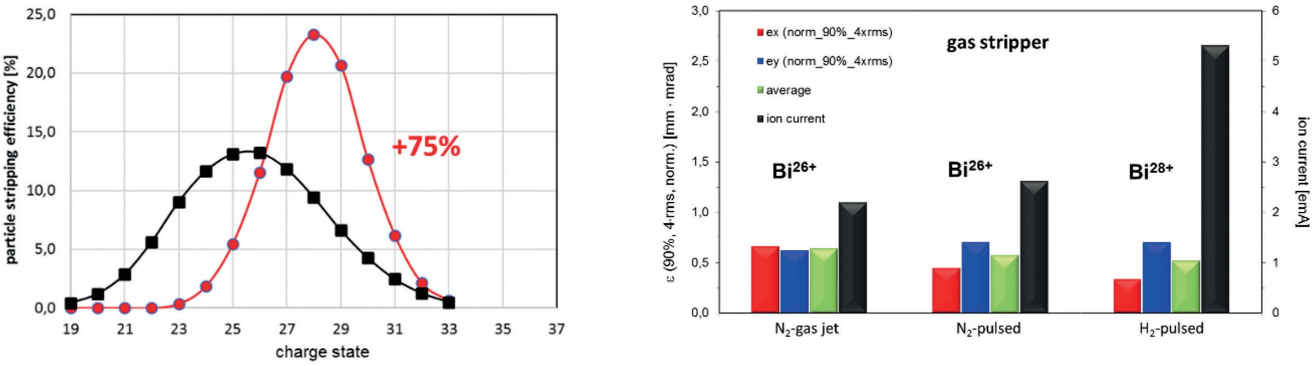


Figure 79. Equilibrium charge state distribution applying N2 (black) and H2 (red) targets after stripping of Bi-beam at 1.4 MeV/u (left); related measured beam emittance for the equilibrium charge states.

In order to characterize the stripping performance, the absolute stripping efficiency into the desired charge state is a key indicator. A sufficient charge state resolution is required to enable highest intensities in the desired charge state. As shown in Figure 79 (left), the stripping efficiency for high intensity Bi-beam could be improved significantly. Initially a N_2 gas jet target has been compared with a N_2-pulsed gas stripper target, without any significant difference. Applying a high density H_2-target (instead of a N_2-target) the yield is 75% higher, the maximum average charge state shifts by two charge units. For the equilibrium charge states (26+ and 28+) the transversal beam emittance (Figure 79, right) was measured at an electrical beam pulse intensity of 4.0 emA (Bi^{4+}). Surprisingly horizontal beam emittance is two times lower for the hydrogen target, while the vertical emittance is slightly higher. This effect has been observed also with other heavy ion beam species, in particular for stripping of uranium beams at 1.4 MeV/u [1-5].

Front to end UNILAC heavy ion beam investigations

One of the crucial quantities to characterize the high-current capability of a synchrotron injector is the horizontal beam emittance at a fixed beam intensity [6-9]. Checking FAIR-injector mode capabilities, the transversal beam emittance for high current beam (Bi^{28+}) has been measured (see Figure 80, left). The horizontal high current (5.5 mA) Bi^{28+}-beam emittance growth inside the Alvarez was measured to be 50% (rms) [1], while vertical emittance is growing by more than a factor of two. As shown in Figure 80 (right) the measured Bi-beam current (electrical) at the end of the transfer line to the SIS18 is 2.5 times higher applying a hydrogen-stripping target instead of nitrogen stripping at 1.4 MeV/u. A much lower horizontal emittance, in comparison to the vertical plane, has been observed. For the high current beam dynamics layout of the gas stripper section, an enlarged vertical beam envelope in the interaction zone is foreseen, resulting also in an enhanced beam emittance growth due to strong particle straggling. Taking into account the increased defocusing effect of the space charge forces due to the higher electric beam current, the horizontal beam level must also be reduced, resulting in smaller horizontal beam emittances. Thus, horizontal beam brilliance at 1.4 MeV/u simply scales with the pulse current. As a result, the horizontal beam brilliance, which is decisive for the filling of the SIS18, is almost three times higher compared to the Bi-beam stripped with the nitrogen target.

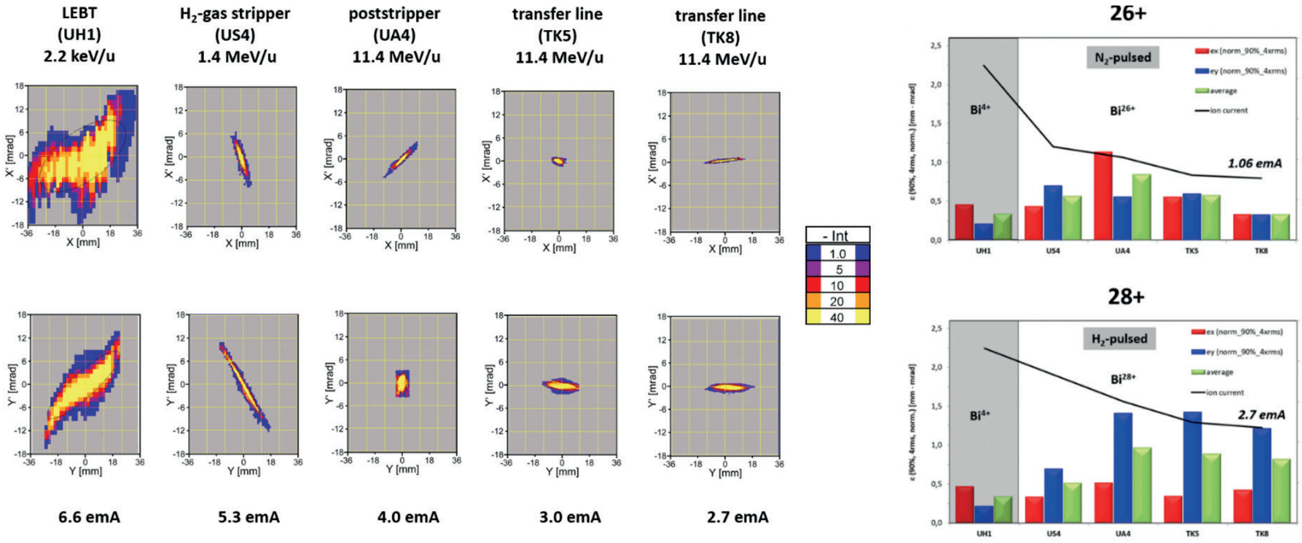


Figure 80. Measured high current Bismuth beam emittance along GSI-UNILAC (left), applying pulsed hydrogen gas stripping [18] to the equilibrium; comparison of emittance measurements applying N2- (right, top) and H2-gas stripping (right, bottom).

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13.3.3 SIS18 Maschine Studies

V. Kornilov, D. Ondreka, P. Spiller, J. Stadlmann

During the FAIR parameter campaign bismuth with intermediate charge state of 26+, as foreseen for FAIR booster operation, could be accelerated with intensities of about 2e10 particles per spill. With the stripping in the transfer channel about 2e9 Bismuth ions with charge state 68+ could be accelerated and extracted. This corresponds with the performance achieved with different heavy ion species in the past.

There was no dedicated beam study campaign under the responsibility of the machine coordinators in 2020. However, we did manage to do a few machine studies during the engineering run.

Slowly extracted Protons and highest SIS18 energy

In preparation of the experiments in 2021 and beyond, protons were accelerated to energies beyond 3 GeV and extracted slowly. This had only been done once previously in the year 2000.

To accelerate protons, we apply a scheme where we move the transition point (γ_t) of the machine during the acceleration ramp to avoid transition crossing. This is implemented by breaking the machine symmetry from 12 to 6 utilizing the two independently powered circuits for both F and D quadrupoles. The change of the transition point comes at the price of acceptance. The optics at flattop is not suitable for slow extraction.

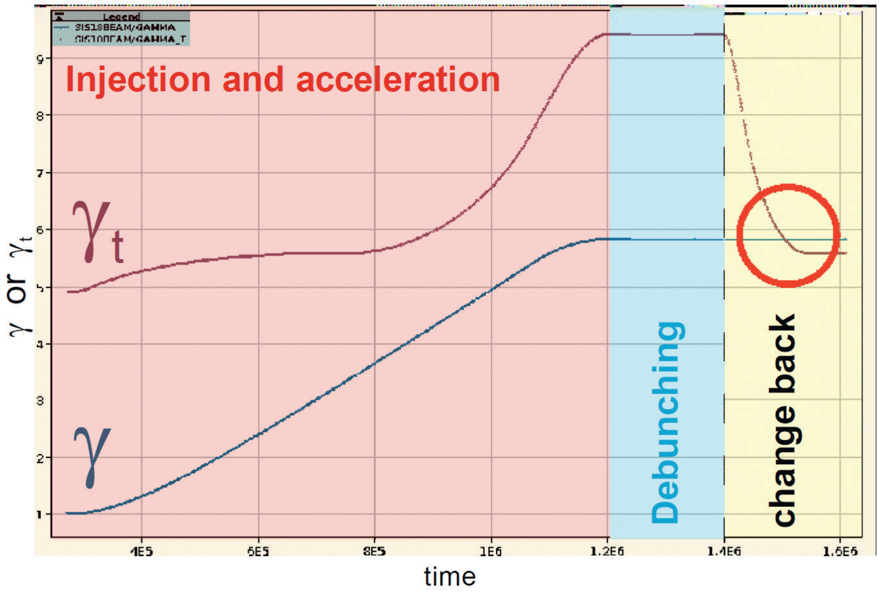
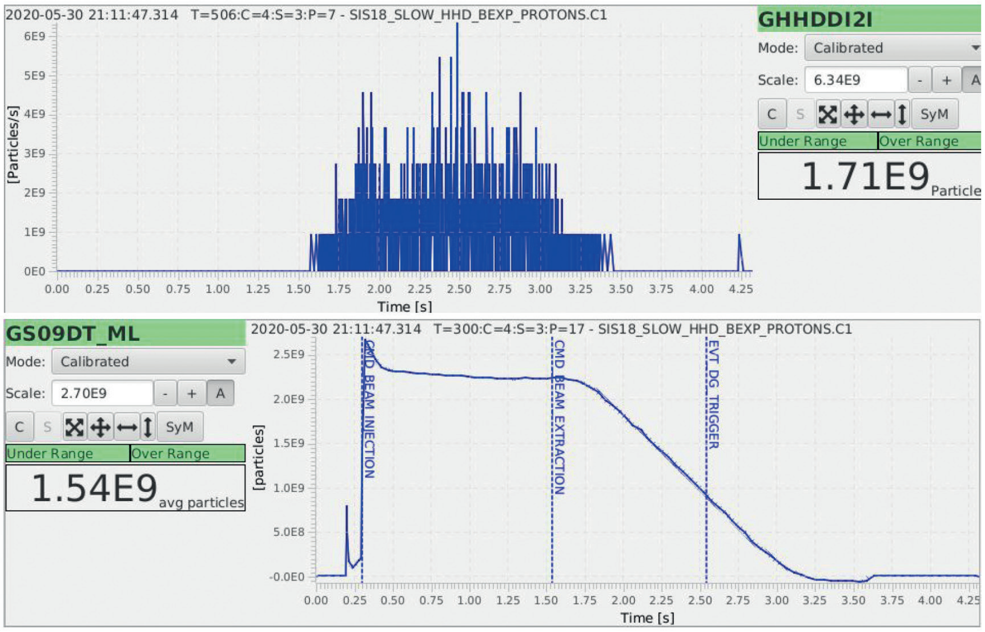


Figure 81. Graph of the cycle used for acceleration and slow extraction of protons with 4.5 GeV/u. The cycle starts like the usual proton cycle with moving γ_t to avoid transition crossing (red area). On flattop the beam is debunched (blue area) and subsequently the optic is changed back to the standard slow extraction optic (yellow area).

In Figure 81 the beam γ and γ_t of the lattice of the used cycle are depicted. The beam is first accelerated normally. In the second half of the ramp, the g_t is moved to avoid transition crossing during acceleration. On flattop, the beam is debunched and subsequently the optics is changed back to be suitable for slow extraction.



2020-05-30 21:11:47.314 T=506:C=4:S=3:P=7 - SIS18_SLOW_HHD_BEXP_PROTONS.C1

GHHDDI2I

Mode: Calibrated

Scale: 6.34E9

1.71E9 Particle

GS09DT_ML

Mode: Calibrated

Scale: 2.70E9

1.54E9 avg particles

2020-05-30 21:11:47.314 T=300:C=4:S=3:P=17 - SIS18_SLOW_HHD_BEXP_PROTONS.C1

Figure 82. Beam current over time measured with transformer (GS09DT_ML, lower part) and extracted particles over time measured with a detector (ionization chamber, GHHDDI2I) at the beam dump (HHD) for a Proton beam of 4.5 GeV/u. Note that the detector at HHD was not calibrated during the measurement.

Figure 82 shows the proton beam current over such a cycle and readings of a particle detector at the beam dump HHD during slow extraction. It could be shown that slow extraction of protons at highest rigidity is possible and as a results experiments using this newly established scheme are scheduled for 2021 and beyond.

Measurements of longitudinal and transverse emittance preservation in SIS18

Longitudinal and transverse beam emittances were tracked during the energy ramp and during the bunched beam storage at the injection energy. Bunches in 1RF and in 2RF buckets were measured and compared.

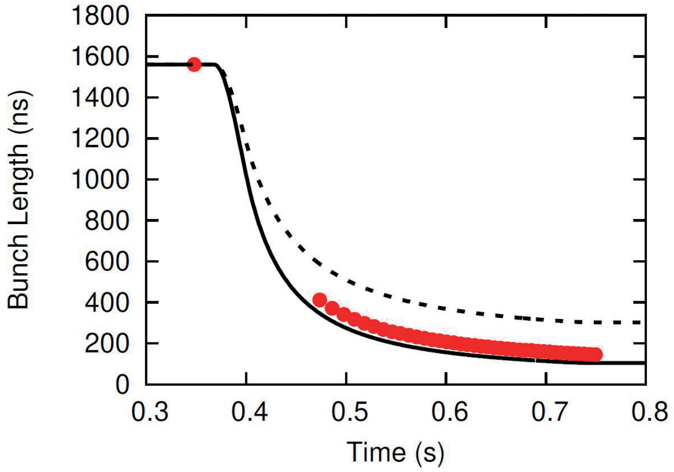


Figure 83. Time evolution of the bunch length during the ramp. Every dot is the 4σ bunch length from an fast current transformer profile. The solid line shows the theoretical dependency for the perfect longitudinal emittance preservation. The dashed line corresponds to a fixed bunch length in meters (no shrinking).

As an example, Figure 83 shows the time evolution of the bunch length in 1RF during the ramp. The observed beam length blowup is ~20 %, which corresponds to a longitudinal emittance blowup of ~40 %. Measurements of the transverse emittances indicated good emittance preservation, both for the beam storage and for the ramps. Beam losses and the related beam profiles were analyzed for the beam storage and for the distinctive loss at the ramp beginning (the “kink”).

13.4 Accelerator research & developments

13.4.1 General R&D for accelerators

Development of new ion species for accelerator operation from high current ion sources

Authors: A. Adonin, R. Hollinger

In 2020 the ion source department was requested to develop high current ion beams of three new ion species: ^{141}Pr, ^{160}Gd and ^{170}Er in order to fulfil the requirements of future high energy experimental programs (Nuclear physics/spectroscopy, NUSTAR). For first tests the electrodes for all three elements have been manufactured and delivered by Fa. HMW Hauner. The electrodes have natural isotope composition.

The tests have been performed at Terminal North with VARIS (vacuum arc ion source) in September-October 2020 during the shutdown period. The operation was with a repetition rate of 1 Hz. The required by HSI-RFQ ion charge state for all three elements is 3+, due to the maximum mass over charge ratio of 65. The measurements have been performed using two different settings in LEBT (low energy beam transport line) between operation Terminal North and HSI-RFQ: settings for mono-isotope/enriched materials and settings for natural poly-isotope materials. For mono-isotopes LEBT has been set for best transmission and maximum ion beam current in UH1-section. For poly-isotope elements a clear separation of the desired isotope in the beamline is required. Therefore, it was necessary to use a special focusing and slits in LEBT. That resulted in attenuation of the ion beam intensity. The following Table 3 contains the results of the tests.

Element:	Praseodymium	Gadolinium	Erbium
Isotope:	^{141}Pr (mono-isotope)	^{160}Gd (22% in nat. comp.)	^{170}Er (15% in nat. comp.)
Ion charge state:	3+	3+	3+
Repetition rate/pulse length:	1 Hz / 0.5ms	1 Hz / 0.45 ms	1 Hz / 0.45 ms
Operation stability:	excellent *	good **	good **
Ion beam current in front of the HSI-RFQ:	15 mA	1 mA (15 mA)***	0.6 mA (10 mA)***
Number of particles in 100 µs pulse:	$3{\cdot}10^{12}$	$2{\cdot}10^{11}$ $(3{\cdot}10^{12})$***	$1.2{\cdot}10^{11}$ $(2{\cdot}10^{12})$***
Operation lifetime of a single cathode:	> 10 hours	> 12 hours	> 8 hours

Table 3. Results of the tests with Praseodynium, Gadolinium and Erbium.

* pulse-to-pulse intensity fluctuations are less than 10%;
** pulse-to-pulse intensity fluctuations are less than 15%
*** values in brackets correspond to expected values for beam current and particles number with enriched material, if available on market

Praseodymium has shown an excellent performance and extremely stable operation. The temporal profile of the beam pulse was very smooth and pulse-to-pulse intensity fluctuations were below 10%. Praseodymium is a mono-isotope (^{141}Pr) element. The beam current of Pr^{3+} ions reached in UH1-section has exceeded 15 emA, that corresponds to 3·10^{12} particles in a 100 µs pulse.

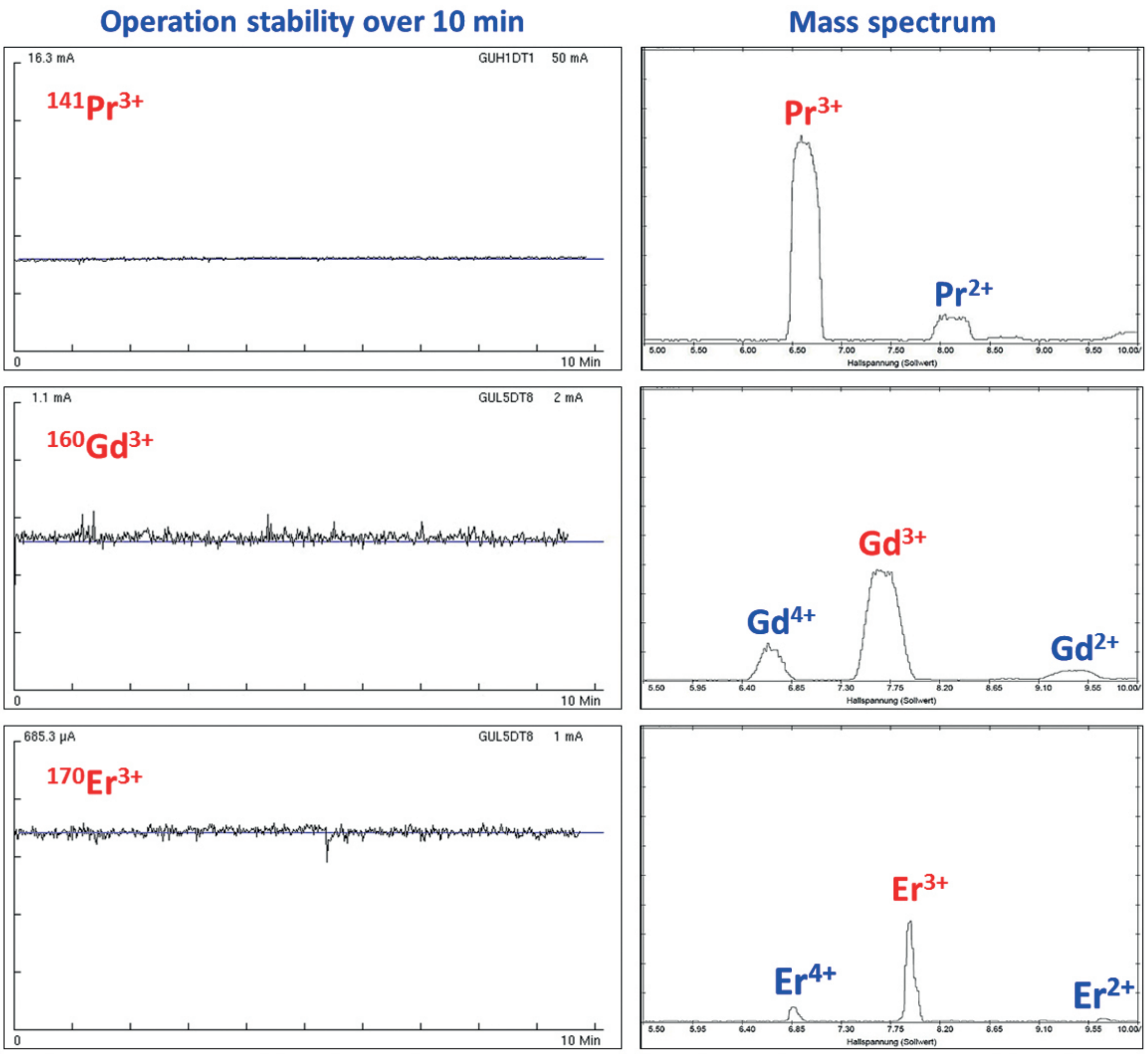


Figure 84. Operation stability over 10 min and mass-spectra for Pr, Gd and Er.

Gadolinium and Erbium are poly-isotope elements containing in the natural composition 22% of ^{160}Gd and 15% of ^{170}Er respectively. Both elements have shown good and stable performance with pulse-to-pulse intensity fluctuations below 15%. It was possible to reach 1 emA and 0.6 emA in UH1-section (that corresponds to 2·10^{11} and 1.2·10^{11} particles in front of the HSI-RFQ in 100 µs beam pulse) for ^{160}Gd^{3+} and ^{170}Er^{3+}, respectively, obtaining a clear separation of other undesired isotopes. Using the beamline settings for enriched materials is was possible to obtain 15 emA and 10 emA for Gd^{3+} and Er^{3+}, respectively. Operation stability over 10 minutes as well as ion charge states distribution for all three elements are shown in Figure 84.

In conclusion, one can state that three new ion species: ^{141}Pr, ^{160}Gd and ^{170}Er were successfully developed for production of high current ion beams for future beamtime operation.

Optical emission spectroscopy and a microwave shielded oven for ^{48}Ca ion beam production with ECRIS

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

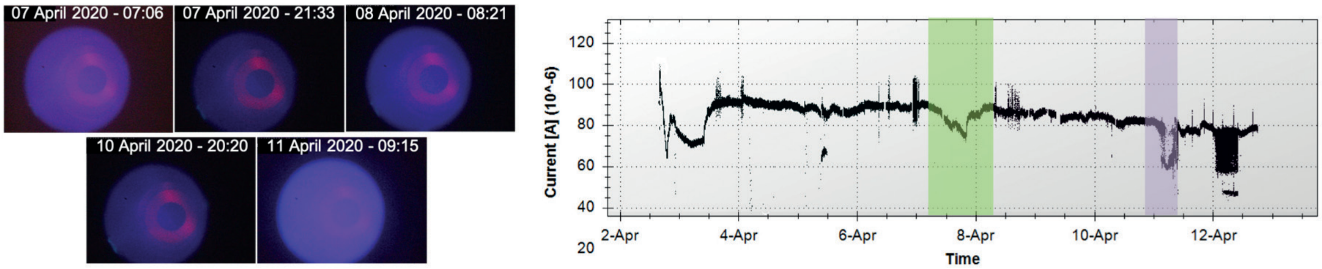


Figure 85. (left) Plasma images recorded at the CCD camera when the optimizations of the ECRIS were requested and (right) $^{48}Ca^{10+}$ intensity measured at the current transformer for 10 days.

The CAPRICE ECRIS installed at the High Charge Injector (HLI) of GSI produces highly charged ion beams from gaseous and metallic elements. A high demand of metal ions comes from the uclear physics, materials research, and Super Heavy Element research (SHE), and the most requested element, besides ^{50}Ti, is ^{48}Ca. When this chemical reactive material is deposited inside the plasma chamber at internal components, the stability can be compromised. Furthermore, it is difficult to find a working point to guarantee a long-term stability as the oven response time and the reaction of the ECRIS are relatively slow. The monitoring by using an Optical Emission Spectrometer (OES) facilitates immediate reactions whenever plasma instabilities occur. For this reason, a real-time diagnostic system based on an CCD camera and an OES has been installed at the ECRIS at HLI for routine operation. The use of plasma images shown in left Figure 85, together with an OES as a diagnostic tool were useful to recover the source performances much faster during the metallic ion beam production whenever optimizations, like underlined in right Figure 85, are required or instabilities occur. This result has been confirmed during the ^{48}Ca runs in 2020. The monitoring of the spectral components at certain visible wavelengths, as shown in Figure 86 left, prevented excessive optimization time. The measured spectra revealed a parasitic oven heating by coupled microwaves often compromising the ion source performance. Therefore, a tungsten grid has been installed to shield the oven orifice from the coupled microwaves as shown in right Figure 86. The grid shielding of the oven head has improved the Ca ion beam production by an ECRIS in terms of stability, intensity and material consumption since the parasitic heating of the ceramic insulating material inside the oven head is strongly reduced. [F. Maimone, J. Mäder, A. Andreev, R. Hollinger, R. Lang, P. T. Patchakui, and K.Tinschert, Proc. of the ECRIS20 - 24th Workshop on ECRIS, 28-30.09.20, MSU, USA].

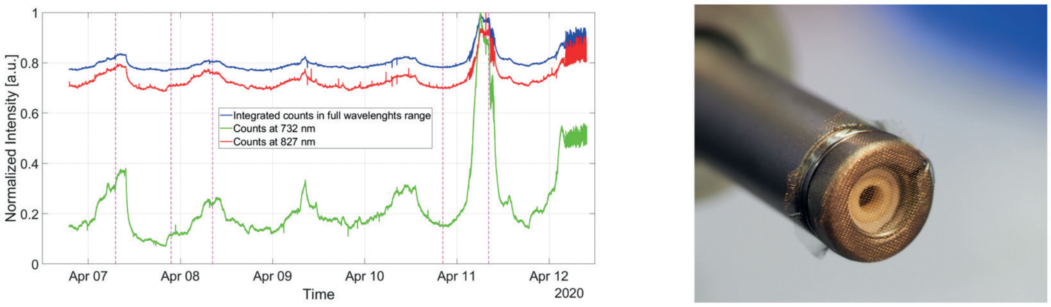


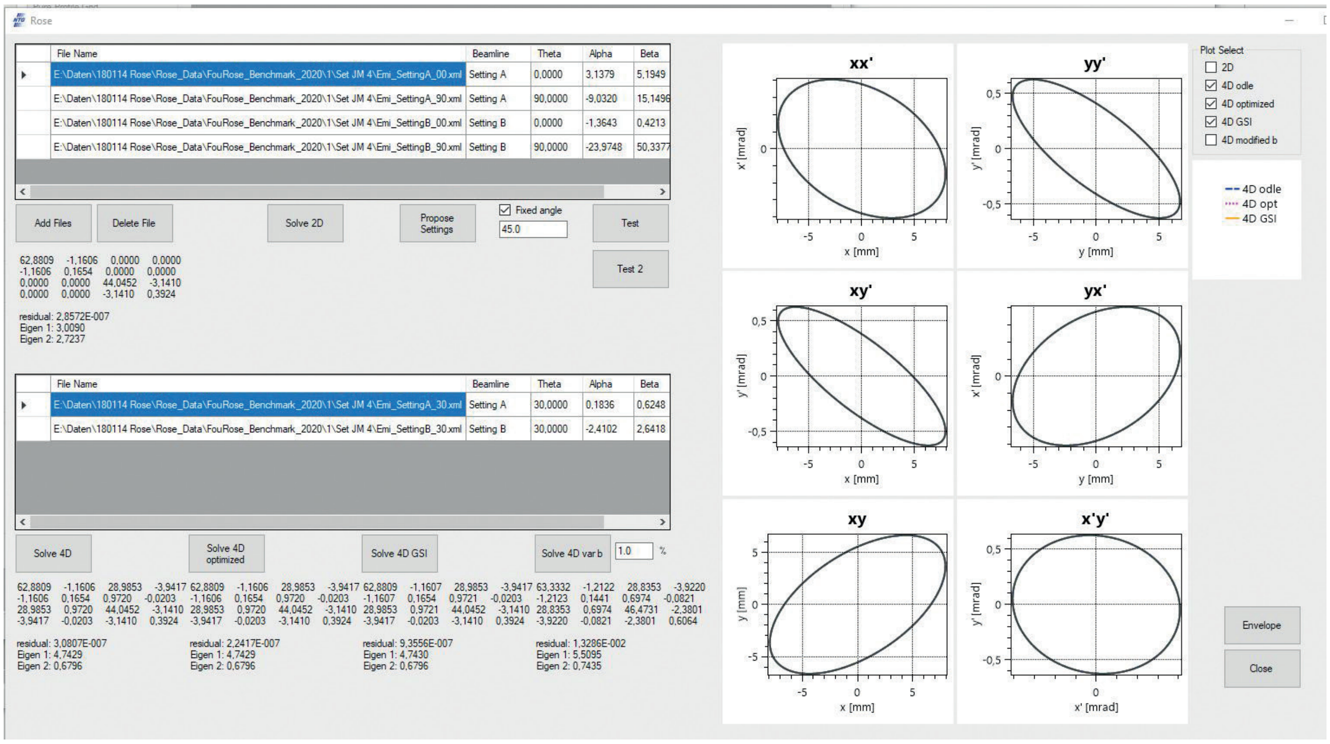
Figure 86. (left) Normalized light intensity at different wavelengths recorded for 5 days and (right) microwave shielding grid at the oven orifice.

Development of FOUROSE and site acceptance test preparation

Coordination: Lars Groening GSI
Authors: M. Maier, M. Bauer, A. Bechthold (TG Neue Technologien GmbH & Co. KG, Gelnhausen, Germanyd , X. Du, T. Engert, J.Maus (TG Neue Technologien GmbH & Co. KG, Gelnhausen, Germany), C. Xiao

The detector system ROSE [C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann, Rotating system for four-dimensional transverse rms-emittance measurements: Phys. Rev. Accel. Beams 19, 072802 – Published 19 July 2016.] allowing to perform full 4D emittance measurements on heavy ion beams independent of their energy and time structure, has been built and successfully commissioned in 2016 at GSI in Darmstadt, Germany. This method to measure the four dimensional emittance has then been granted a patent in 2017 [Deutsche Patentanmeldung Nr. 102015118017.0 eingereicht am 22.10.2015 beim Deutschen Patent- und Markenamt Titel der Patentanmeldung: Drehmodul für eine Beschleunigeranlage.]. The inventors together with the Technology Transfer department of GSI have found an industrial partner to modify ROSE into a standalone, commercially available emittance scanner system. This is a three step process involving the hardware ROSE, the standalone electronics ROBOMAT [gefördert durch: Bundesministerium für Wirtschaft und Energie], and the software working packages. This contribution puts focus on the successful development of the 4D software package FOUROSE [Dieses Projekt (HA-Projekt-Nr.: 694_19-14) wird im Rahmen der Innovationsförderung Hessen aus Mitteln der LOEWE, Landes-Offensive zur Entwicklung Wissenschaftlich ökonomischer Exzellenz, Förderlinie 3: KMU Verbundvorhaben gefördert.] and the preparations for the final site acceptance test at GSI.

Development of FOUROSE



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☑ Fixed angle: 45.0

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-1,1606   0,1654    0,0000    0,0000
0,0000    0,0000    44,0452   -3,1410
0,0000    0,0000    -3,1410   0,3924

residual: 2,8572E-007
Eigen 1: 3,0090
Eigen 2: 2,7237
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	File Name	Beamline	Theta	Alpha	Beta
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Solve 4D var b: 1.0 %

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62,8809  -1,1606  28,9853  -3,9417 62,8809  -1,1606  28,9853  -3,9417 62,8809  -1,1607  28,9853  -3,9417 63,3332  -1,2122  28,8353  -3,9220
-1,1606  0,1654   0,9720   -0,0203  -1,1606  0,1654   0,9720   -0,0203  -1,1607  0,1654   0,9721   -0,0203  -1,2123  0,1441   0,6974   -0,0821
28,9853  0,9720   44,0452  -3,1410  28,9853  0,9720   44,0452  -3,1410  28,9853  0,9721   44,0452  -3,1410  28,8353  0,6974   46,4731  -2,3801
-3,9417  -0,0203  -3,1410  0,3924   -3,9417  -0,0203  -3,1410  0,3924   -3,9417  -0,0203  -3,1410  0,3924   -3,9220  -0,0821  -2,3801  0,6064

residual: 3,0807E-007         residual: 2,2417E-007         residual: 9,3556E-007         residual: 1,3286E-002
Eigen 1: 4,7429               Eigen 1: 4,7429               Eigen 1: 4,7430               Eigen 1: 5,5095
Eigen 2: 0,6796               Eigen 2: 0,6796               Eigen 2: 0,6796               Eigen 2: 0,7435
```

Figure 87. A screenshot of our software GUI FOUROSE allows to prepare, perform, evaluate, and plot 4D emittance measurements using the ROSE emittance scanner. Within the depicted evaluation the 4D method developed by GSI and the adaptations of NTG are benchmarked successfully.

The development of the software package FOUROSE started in April on base of the refined algorithm provided by GSI [C. Xiao, X.N. Du, L. Groening, M. Maier, Refining the evaluation of eigen emittances measured by the dedicated four-dimensional emittance scanner ROSE Ms. Ref. No.: NIMA-D-20-00013R2, Nuclear Inst. And Methods in Physics Research, A.] The largest effort went into programming the human machine interface. Followed by the other major issue being benchmarking of the different code parts using old data sets to ensure their mathematic similarity. FOUROSE is performing the tasks of originally three independent scripts. It calculates and suggests the measurement settings needed for a 4D emittance scan based on 2D emittance data. It evaluates and finally plots the obtained results. Figure 87 shows the result of an off-line benchmarking run. The code of GSI and the adaption by NTG to be used in FOUROSE agree very well such that the drawn ellipses are indistinguishable.

Preparation of X3 experimental site

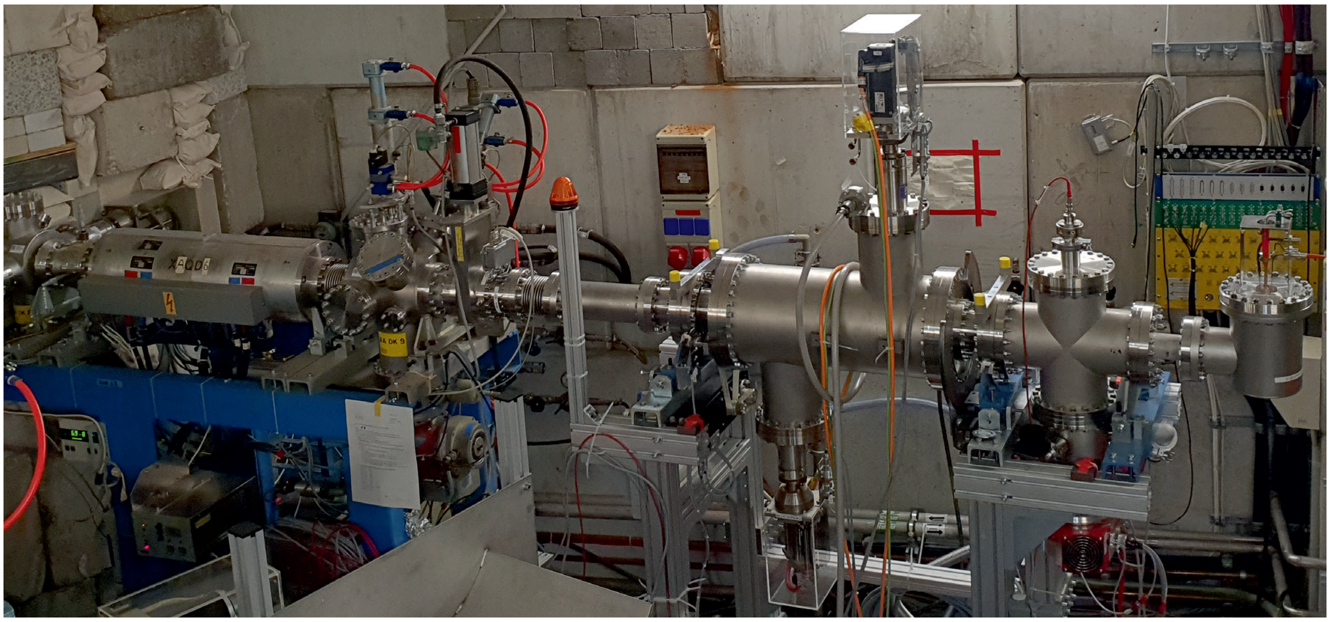

Figure 88. A photograph taken by M. Maier of the beamline UX3 behind the UNILAC comprising from the left a magnetic quadrupole doublet, SEM grid, beam current transformer followed by the detector ROSE, and finally an end cup.

In parallel to the software development, in spring 2020 the experimental beamline X3 behind the UNILAC has been cleared and modified to install ROSE (Figure 88). It was necessary to add an additional beam current transformer in front and an end cup behind ROSE as 100% transmission is a prerequisite for 4D beam emittance measurements.

Outlook

We have received positive response to the requested commissioning and SAT beam time. It will be part of the accelerator-development beam time end of June 2021. This beam time is divided into two parts of five days each to separate commissioning and SAT by two weeks. This is done in order to be able to react to unforeseen circumstances. In parallel, the legal department of GSI together with technology transfer is working on a license agreement with NTG.

13.4.2 Investigation of advanced UNILAC operation modes

Authors: H. Vormann, U. Scheeler, W. Barth, S. Yaramyshev

Set of new HSI-RFQ working point

After shutdown 2017 a strong performance decrease of the RFQ cavity was detected. The exchange of the rods carried out for this reason after beamtime 2019 did not result in a complete recovery of the RFQ-RF-voltage level. In order to be able to continue using the RFQ for accelerating heavy ions, the RFQ-working point was re determined.

So far we had assumed that the design rod voltage of 155 kV for acceleration of U^{4+}-beams has been reached, when the RF pickup chain monitors 8.3 Volts. Already in 2019 we observed that uranium acceleration is possible even with the surprisingly low voltage of only 7.1 Volts. Also during the beam parameter campaign in May 2020 we accelerated $^{209}B^{4+}$ beam with a 6% lower voltage than nominal, without beam quality degradation. Based on multi particle dynamic simulation results, advanced investigations have been conducted in November 2020 with high current argon beam. The simulations predicted that the transmission through the complete HSI should start to decrease significantly when the RFQ voltage is lowered from 100% to 92% of the nominal value.

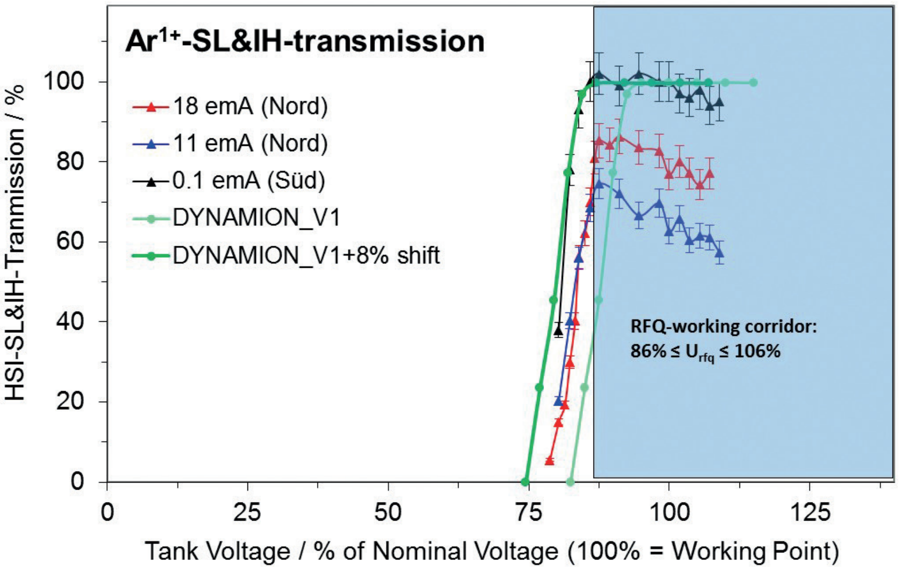

Figure 89. HSI-RFQ beam transmission as function of tank voltage for different Argon beam currents. [1]

It turned out that the RF voltage had to be reduced to 86% of the recent working point value (8.3 V) to meet the starting point of the strong transmission decrease. This allowed us to define a working corridor (marked in blue in Figure 89) and to set a new working point at 89% of the original one of 8.3 V. Obviously we can assume that up to now we would apply approximately 168 kV at a pickup voltage of 8.3 V (Uranium level), while the new Uranium working point at 7.4 V corresponds probably to 150 kV rod voltage.

Additional tests with $^{238}U^{4+}$ (A/q=59.5), $^{181}Ta^{3+}$ (A/q=60.33) and $^{124}Xe^{2+}$ (A/q=62) will be carried out in 2021.

Proton and C^{6+} operation at UNILAC

Proton acceleration in the Alvarez post stripper requires very low RF voltages, as long as the regular synchronous phase of -30° (A1/A2a/A2b) resp. -25° (A3/A4) is applied. To run at these low voltages, the RF transmitters have to be tuned carefully providing for stable and reliable proton beam operation. This strong effort and long lasting tuning procedure can be avoided, when larger negative phases for the reference particle are chosen: For the same peak voltage the instantaneous voltage for the reference particle is then lower ($U(\varphi)=U_{peak}*\cos\varphi$). Accordingly, for the same reference particle voltage higher RF peak voltages can be applied.

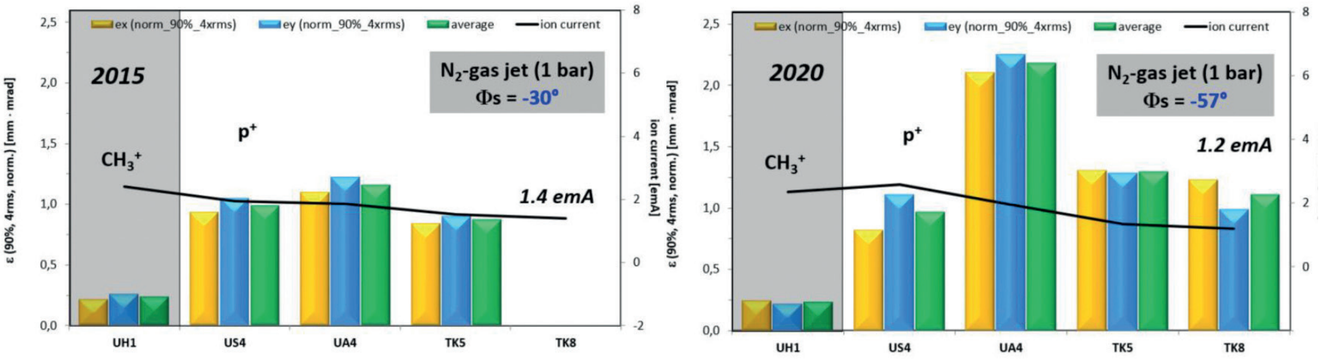

Figure 90. Measured proton beam current and transversal beam emittance along UNILAC for standard synchronous phase of -30° (left) applied at ALVAREZ DTL and for synchronous phase of -57° at a 50% higher RF-tank voltage [2,3].

During the machine experiments in May/June 2020 we investigated high current (2 emA) proton beam operation in the post stripper with RF phases down to -75°. Phase values lower than -65° lead to unacceptable beam quality, a phase value of -57° turned out to be the best compromise: Sufficient beam properties are reached at manageable RF control-voltages of >1.5 V for all Alvarez-tanks. As shown in Figure 90 the beam emittance is increased by almost a factor of 2, while beam transmission is not significantly changed.

The high current proton beam is provided from the High Current Injector (HSI): From the ion source singly charged CH_3 molecules are extracted. After acceleration in the pre-stripper the molecules are cracked into protons and carbon (which is stripped) in the gas stripper section, enabling simultaneous carbon beam operation (C^{6+}) in the poststripper. For further poststripper acceleration the Alvarez dc quadrupoles were adjusted to an average A/q-value of 1.35, sufficient for proton- (A/q = 1) and C^{6+} (A/q =2) operation.

For proper proton beam quality, the gas stripper nozzle pressure must be relatively low (N_2 1000 mbar, while max. pressure is 4000 mbar). With this low gas pressure the yield of highly charged carbon ions (C^{6+}) is low. It is not possible to use lower charged carbon ions, because the Alvarez dc quadrupoles must be adjusted for a low average mass over charge ratio, close to the proton value 1.0 (1.35 was applied as a compromise).

Avoiding strong scattering effects for the proton beam the stripper N_2-target density should be relatively low. In contradistinction, fully stripped carbon ions can only be achieved by high target densities. The challenge for 2021 proton and carbon parallel operation at UNILAC is to choose the target thickness in such a way that both beams in parallel operation are possible.

References

- [1] H. Vormann et al., HSI investigations with 40Ar- beam at the GSI-UNILAC https://www.gsi.de/fileadmin/Beschleunigerbetrieb/Dokumente/2020_UNILAC_Report_20201208_final.pdf
- [2] H. Vormann et al., Machine investigations with 209Bi- and proton-beam at the GSI-UNILAC, https://www.gsi.de/fileadmin/Beschleunigerbetrieb/Dokumente/UNILAC_Report_ACC_Exp_05_06_2020.pdf
- [3] W. Barth et al., LINAC developments for heavy ion operation at GSI and FAIR, 2020 JINST 15 T12012, https://doi.org/10.1088/1748-0221/15/12/T12012

13.4.3 Accelerator Improvement Projects

Introduction

Authors: M. Bai, U. Weinrich

The existing GSI accelerator complex contains the ion sources, the UNILAC, the SIS18, the High Energy Beam Transport Line HEST, the ESR, HITRAP@ESR and - as latest member- the CRYRING@ ESR. All these accelerator sections will remain in operation in the future joint GSI/FAIR accelerator complex and serve all scientific communities of FAIR. Especially in order to improve the beam performance towards the requirements for the new FAIR operation modes several projects were started and are in execution now. Most of these projects are under the leadership of accelerator experts from the business area accelerator operations.

The list of projects under the Accelerator Improvement Project (AIP) is large. It ranges from projects with investment of a few hundred thousands of Euros up to more than 30 million of Euros. Project durations vary from about 2 years up to 10 years. Throughout the year 2020 the focus was on the following projects – out of which only a subset is presented in this Chapter:

1. The development and procurement of an 18 GHZ ECR source in order to generate higher intensities and/or charges states from the High charge injector HLI (High Charge State Injector) of a certain set of ion species.
2. The development and procurement of a reliable and safe technical set up for the pulsed gas stripper using hydrogen as main stripping gas. The use of hydrogen instead of nitrogen as stripping gas demonstrated significantly higher efficiency for the stripping process. For this system also a project review was executed as many interfaces towards controls, safety and building issues need to be evaluated in a joint approach.
3. The upgrade of the UNILAC vacuum control system to the new FAIR accelerator control system standard in order to regain long term reliability, to improve the synchronization of the UNILAC with the SIS18 operation modes and finally to also profit from new features of the FAIR accelerator control system standard.
4. The procurement and test of a First-of-Series (FOS) unit for the new UNILAC poststripper and the planning for the procurement of the series components afterwards. The poststripper acceleration units need to be replaced due to aging problems. In addition, some modifications are required to enable the operation at highest beam intensities required for the new FAIR operation modes of SIS18.
5. The refurbishment of the galvanic workshop equipment and building in order to qualify the copper plating of the very large tanks of the new UNILAC poststripper as well as the complex and heavily packed structures of the FAIR p-Linac. The refurbishment is required to enable the copper plating of all accelerating structures of these two linac projects.
6. The procurement and set up for the advanced demonstrator of a cw-Linac on the GSI campus. This demonstrator aims at qualifying the physics and technology for a cw-Linac which can serve the existing UNILAC user community with dedicated ion beams of higher duty cycle and integrated intensity than the UNILAC.
7. The planning of an additional beamline from SIS18 towards the beam stop HHD with the aim of gaining operation flexibility in terms of fast switching between the HHD beam line and the fragment separator FRS. Also for this system, a project review was executed due to a dense installation of accelerator components and the requirement of rearrangement of shielding walls.
8. The refurbishment of the ESR beam instrumentation equipment to the new FAIR standards in order to assure long term reliability.

9. The digitization of fast ESR analog signals in order to enable the control from the new FAIR Control Center FCC – a building project in execution at the moment.
10. The upgrade of the RF system of the CRYRING@ESR in order to allow faster ramping up in energy for beam from the local injector to gain integrated intensity for ions beams with very short lifetimes.
11. The procurement of an EBIT source for the local injector of the CRYRING@ESR in order to significantly increase the primary intensity for light, highly-charged ions.

In order to assure transparency and adequate follow up of the projects a series of quarterly report meetings on all major ACC projects was established. Guided by the Accelerator Project Office a reporting standard was developed which fits this purpose. This reporting Standard contains:

- a compact project description
- a progress overview since last meeting
- planned and reached milestone s-curves
- charts on overall and yearly financial planning and spending
- critical issues and the corresponding mitigation actions are part of this reporting.

The process of presenting and discussing the major projects of business area accelerator operations in this quarterly reporting format is well established by now. Four meetings took already place and the reporting standard is well understood and followed by the project leaders. The transparency for steering purposes of the projects progress is significantly increased by now.

18 GHz ECRIS Upgrade

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

In the reporting period, the formal approval of a cooperation agreement between the University of Jyväskylä and GSI was achieved. It defines the transfer of knowledge and joint R&D on the investigation and future development of a high performance ECR ion source (ECRIS, Electron Cyclotron Resonance Ion Source) which is in successful operation at the JYFL Accelerator Laboratory for several years [see K. Tinschert, F. Maimone, R. Lang, J. Maeder, P. Patchakui; 18 GHz ECRIS upgrade, GSI-FAIR Scientific Report 2019, p.139, DOI:10.15120/GSI-2020-00416, and references therein].

The original technical drawings of this ECRIS were thoroughly investigated in order to identify potential technical improvements. Construction details were discussed and clarified in the framework of the cooperation. The drawings were accordingly modified, converted and adapted to the requirements of the GSI accelerator operation.

The specifications for the two main assembly groups, the hexapole for the radial magnetic confinement, and the solenoids for the longitudinal magnetic confinement are in progress. In order to investigate the complex magnetic systems, which is the result of the superposition of radial and longitudinal magnetic fields, computer simulations are underway. Their goal is the further optimization of the magnet system e.g. by using innovative permanent magnet materials and technologies.

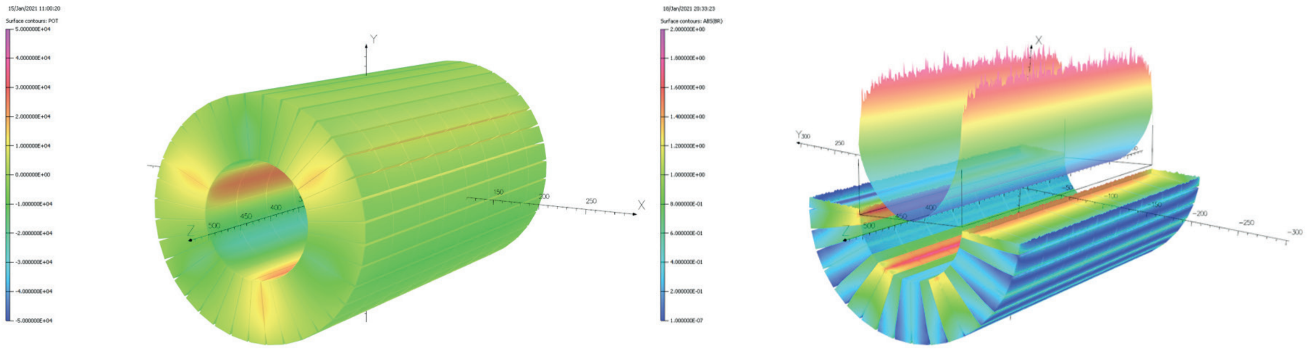

Figure 91. (left) 3D magnetic field distribution and (right) magnetic field along a horizontal cut-plane.

The magnetic field generated by a 36 segments (remanence field Br = 1.349 T and coercivity HcB = 1034.5 kA/m) Halbach-Type hexapole has been simulated with Opera Simulation Software [https://www.3ds.com/products-services/simulia/products/opera/]. The 3D magnetic field distribution together with a horizontal cross section are shown in Figure 91.

The results confirmed that around 1.43 T radial field at the plasma chamber wall can be achieved with this configuration. The specifications for the hexapole will be defined according to the results of these magnetic field simulations.

Progress on Design and Construction of the new post-Stripper section of the UNILAC

Head: Lars Groening
Authors: S.Mickat, M. Heilmann, L. Groening

The Alvarez 2.0 DTL will replace the existing post-stripper DTL of the GSI UNILAC [1]. The first cavity section of the new post-stripper Drift Tube Linac (DTL), the Alvarez 2.0 FOS (First of Series), was tested successfully applying low level radio frequency (LLRF) to the cavity prior to copper-plating [2].

Another focus was on the preparation of the high power RF (HPRF) tests, which are planned in 2021 to qualify the design for the tendering of the series:

- endplates, tank section, and spacer ring were plated in-house [3]
- add-on parts, e.g. tuners and half drift tubes, were produced in-house
- 11 drift tubes without magnets and all add-on parts were Cu-plated externally
- infrastructure measures were carried out at the test stand, e.g. for media supply, for controls and measurement cables, and for RF-supply, etc.

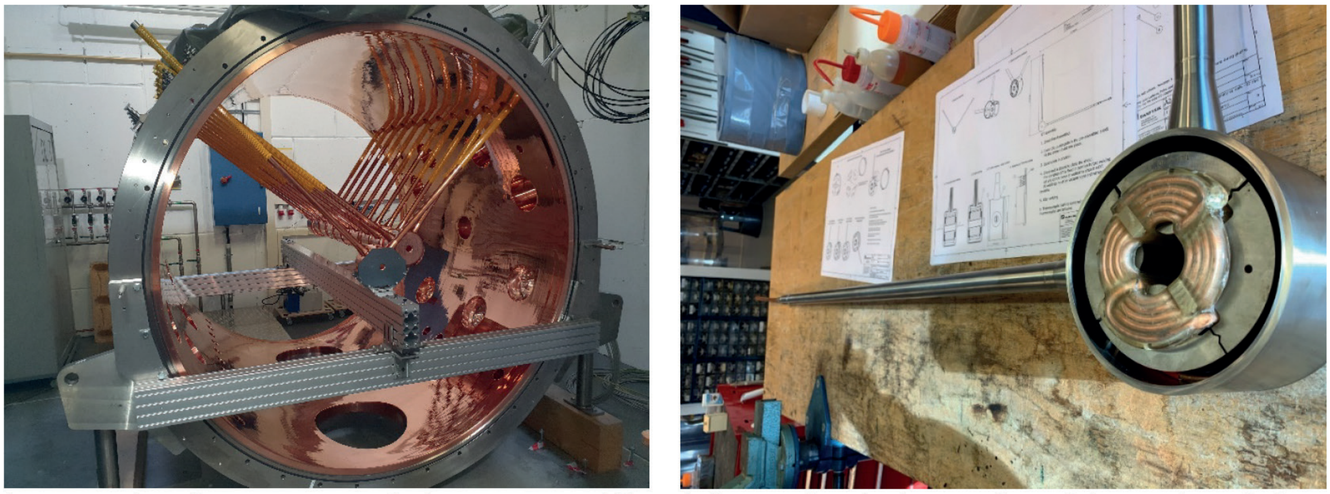

Figure 92. The Alvarez 2.0 FOS during pre-assembling (left). Testing the integration of the quadrupole into the drift tube @Danfysik (right, courtesy of Danfysik A/S).

Further progress was achieved concerning the quadrupole development and its integration into the drift tube (Figure 92). In April 2020 the final design review (FDR) was accepted and Danfysik A/S has started production of magnet and drift tube as proto-types. The final mechanical integration of both components is planned for Q1/2021. Its delivery is expected in Q2/2021. In parallel the procurement of a corresponding magnet power supply has been started.

Positive feedback on the progress of the FOS project was again received from MAC23 with the recommendation to keep the timeline of the Alvarez 2.0 project as short as possible. It was agreed to expedite the tendering of the series components like tank sections and endplates: in 2021 the call for tender will start, such that early in 2022 the order for series production could be placed almost simultaneously to the completion of the HPRF tests.

CERN galvanic experts have been contacted in order to survey the options for a collaboration aiming at external Cu-plating of all post-stripper components except the cavity mantles and end plates. From technical point of view the framework for a collaboration has been set. A contractual collaboration agreement is in preparation.

References

- [1] Mickat, S. et al.: Progress on the Alvarez 2.0 DTL post-stripper section of the UNILAC, GSI Report (2017)
- [2] Heilmann M. et al.: to be published in the Proc. of the IPAC 2021 Conf.
- [3] Walter, G.: this report

Progress of the Pulsed Hydrogen Gas Stripper

Head: Lars Groening
Authors: P. Gerhard, M. Maier

Heavy ion beams provided by UNILAC and SIS18 will account for the majority of beams used in FAIR. High current beams of heavy ions are available from the high current injector HSI. Behind the HSI stripping by a continuous nitrogen jet target is applied. Beam intensities can be increased by more than 50% by using hydrogen as stripping gas [see Scharrer, P.; et al. A Pulsed Gas Stripper for Stripping of High-Intensity, Heavy-Ion Beams at 1.4 MeV/u at the GSI UNILAC. Proc. HIAT'15, Yokohama, Japan, Sep. 2015, paper TUA1C01, pp. 144-147, and Scharrer, P.; et al. An Upgrade for the 1.4 MeV/u Gas Stripper at the GSI UNILAC. Proc. IPAC'16, Busan, Korea, May 2016, pp. 1394-1396. DOI:10.18429/JACoW-IPAC2016-TUPMR058]. In consequence, the gas load had to be reduced. This was achieved by introducing fast valves, which deliver short gas pulses synchronised with the beam pulse.

Since 2019, the project concentrates on turning the experimental setup into a system suitable for regular operation. The main challenges are the safety issues from using hydrogen and the integration into the accelerator control system. Short-term operation of the experimental setup with hydrogen at the UNILAC is continued.

Operating setup

In 2019 a draft technical and baseline safety concept was developed and released by end of the year [Gerhard, P. ; et al. Pulsed Gas Stripper Development. GSI-FAIR Scientific Report 2019 DOI:10.15120/GSI-2020-00416]. This was presented to the main GSI stakeholders in February 2020 and generally approved, achieving the basis for a comprehensive risk assessment by an external expert company, representing in turn a major milestone. A two-day on-site meeting with the expert was held as kick-off in September. The revised draft of the safety concept was presented to the involved departments and approved for elaboration. The draft was improved and detailed based on the feedback from the expert company until end of the year. During this process, some changes to the technical concept were agreed upon. The review concluded in December by issuing a preliminary expert advisory opinion. Finalisation could not be reached due to the complexity of the project and time constraints, leaving some details about the technical implementation unresolved for the time being. However, this does not imply relevant delay for the project's progress.

Equipment upgrades, alternative valves, and beam time

For the final explosion safety document, possible sources of ignition have to be tested at the external company. In order to facilitate the transfer of the equipment and the operation on their testing site, significant enhancements of the experimental setup had to be initiated. These enhancements will also facilitate operating the experimental setup alternately at the accelerator and at the gas stripper test stand located on the ESR roof. Enhancements comprise transport and handling aids, instrumentation, and additional valve test setups. Essential parts are a highly customised flight case to provide permanent housing for the complete main control setup of the gas stripper as well as a safety gas cabinet for use at the UNILAC.

As the originally used fast petrol valves proved unsuitable for long term operation, they have been replaced by CNG valves [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]. Because the CNG type is the only commercially available valve established for use in the gas stripper up to now, efforts were made proactively to discover alternative valves. Another manufacturer could be found in 2020, offering valves originally based on space technology. Prototype valves of two different kinds were ordered, one of them being specially adapted to the gas stripper application. They are now being evaluated.

In May 2020, the pulsed gas stripper was operated for a machine beam time. During the preparation, some technical improvements have been implemented, especially a safety housing for the gas control and hydrogen supply was designed, constructed and put into place. Moreover, the safety technical expertise on explosion safety for the experimental test setup was updated according to the current operating conditions.

Outlook

The technical concept has to be adapted in accordance with the draft safety concept. During this process, the unresolved implementation details will be tackled. Regardless of the preliminary character of the advisory opinion, both technical and safety concept will afterwards be presented to a notified body for provisional approval. Based on a positive feedback, project planning will be updated and procurement may proceed.

Advanced Demonstrator testing infrastructure

Coordination: W. Barth (JGU Mainz & GSI)
Authors: M. Miski-Oglu, W. Barth, M. Basten, C. Burandt, F. Dziuba, V. Gettmann, T. Kürzeder, S. Lauber, J. List, S. Yaramyshev

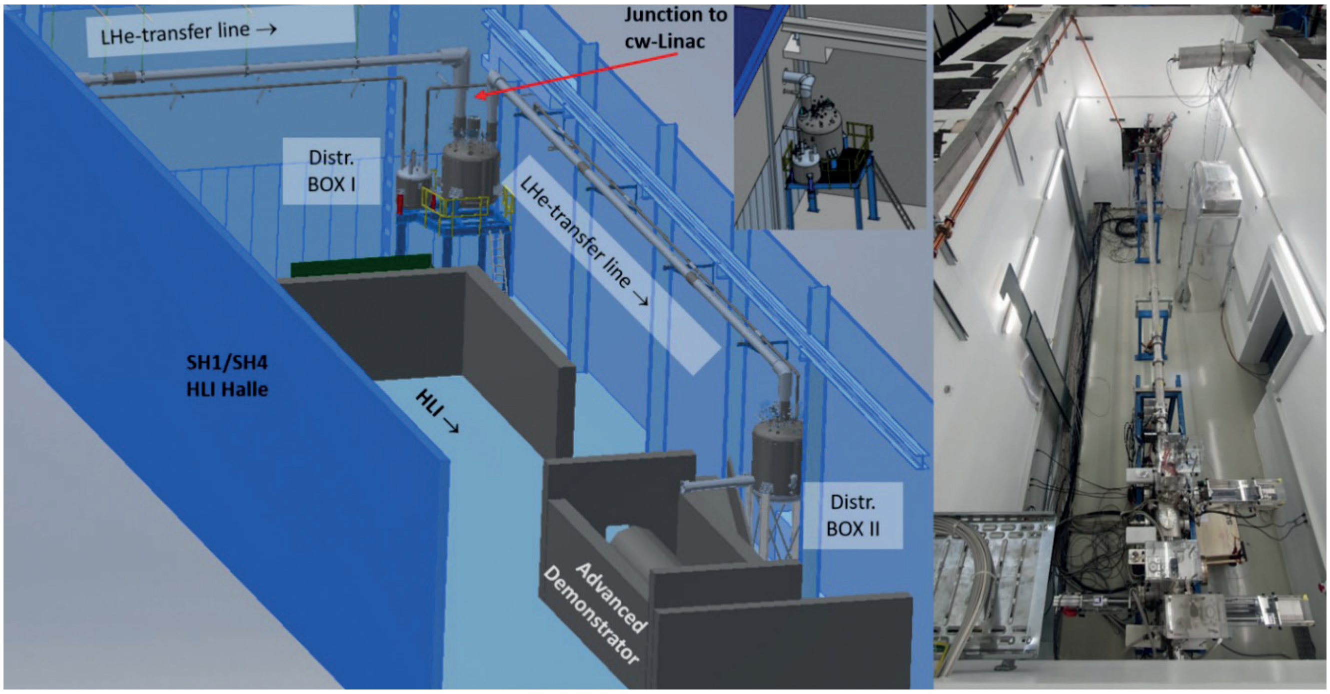

Figure 93. 3D Model of the Helium infrastructure for the cw-Linac and its test area (left). The radiation protection shelter with the newly installed beamline and a beam diagnostic bench is shown on the right side.

In 2020, the design of the first of prototype cryogenic module (Advanced Demonstrator) has been finished. This standard module is equipped with three superconducting (sc) acceleration Cross bar H-mode (CH) cavities CH0-CH2 and a rebuncher cavity as well as two sc solenoids for transversal beam focusing. The manufacturing of the cryostat started and delivery is scheduled for May 2021. The rebuncher cavity is also in the manufacturing process and delivery is announced for the 3rd quarter of 2021. All sc cavities (CH0-CH2) are already fabricated, the rf tests are running. Another important milestone was the successful rf-performance test of the rf-power coupler prototype. After this the series production of 22 ceramic rf-windows started, which are scheduled for delivery in the 2nd quarter of 2021. For stable 4 K operation of the entire cw-Linac HELIAC (HElmholtz LInear ACcelerator) a cryo plant with 240 W 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 superconducting SIS100 dipole magnets. After the magnet testing will be finished, the cryo plant is foreseen to supply the HELIAC. Figure 93 left shows a 3D model of the newly installed Helium transfer lines and the distribution boxes in the "GSI-Stripperhalle" SH1/SH4. The distribution box I guides the helium either to the test area or to the installation side of the HELIAC in the neighboring SH2/SH3 hall. The distribution box II supplies the test area with liquid helium. The commissioning of the He-supply infrastructure has been accomplished in the 3rd quarter of 2020. In preparation for further beam test activities, the beamline, which connects the "GSI-HochLadungsInjektor" (HLI) with the testing area, was installed. The photograph on the right hand side of Figure 93 shows the beamline in the radiation protection shelter, initially instead of the cryogenic module a long vacuum pipe is installed. The beamline comprises current transformers, a pair of phase probes for TOF measurement of the incoming beam energy, quadrupole and two steering magnet pairs enabling transversal matching and a 4-gap rf-buncher cavity for longitudinal matching. Furthermore, for beam-based alignment of the cryogenic module new collimating slits (in horizontal and vertical plane) in front of the test area were installed. The slits cut out the beam halo and potentially can produce a pencil like beam. The beam diagnostics bench at the end of the beamline (inside the protection shelter) is equipped with current transformers, phase probe pairs for TOF measurement of the outcoming beam energy, a slit-grid device for transversal emittance measurement, a bunch structure monitor (Feshenko monitor) for measurement of the longitudinal beam profile. This setup allows for complete 6D characterization of the beam. The entire beam line together with the beam diagnostic bench was successfully commissioned with beam during the engineering run in November 2020. Altogether, the achievements described above, are important steps toward the upcoming full performance test of the prototype cryo module (Advanced Demonstrator) with beam, scheduled for June 2022.

Status of the new HHD beam line

Author: C. Hessler

The GSI accelerator complex suffers from the fact that the SIS18 beam dump located at the HHD beam line is not reachable, when the fragment separator (FRS) is served with beam. The reason is, that the switching magnet GTS3MU1, which is part of FRS, cannot be pulsed due to its large inductance. Therefore the beam direction cannot be switched between FRS and HHD from one cycle to another. The consequences are that the set-up of the SIS18 extraction for beams to other experiments – which requires the beam sent to the HHD dump – cannot be executed during FRS operation and vice versa. Furthermore, HHD cannot be used for machine studies or future SIS18 high-intensity investigations in preparation for FAIR operation, while FRS is running in parallel.

To overcome these limitations, it has been proposed [1] to reroute the HHD beam line in such a way that it bypasses the magnet GTS3MU1, which would enable parallel operation of FRS and HHD. In this scenario, the HHD beam line branches off from the transfer line to the target hall and ESR downstream the present position of GTS1MU1. The beam is then transported to the existing HHD beam dump by using three quadrupoles and an additional dipole magnet. While the switching magnet, the quadrupoles and steering magnets for this new beam line will be reused existing magnets, a suitable dipole is not available and must therefore be procured. A magnet type, which is also used once at FAIR, has been chosen and ordered to profit from production synergies and common spare parts. Furthermore, four new power converters are required as well as vacuum equipment and beam diagnostics.

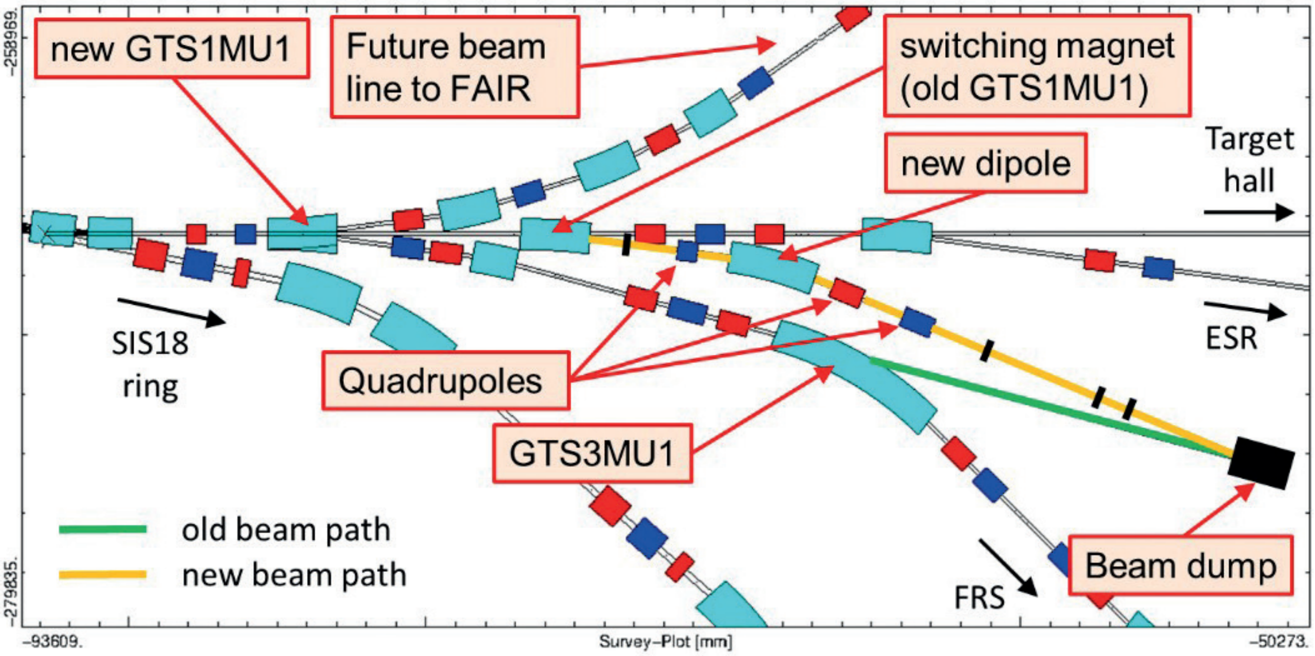

Figure 94. Layout of the new HHD beam line shown as yellow line compared to the existing beam line in green colour.

However, the major challenge of this project is to integrate this new beam line into an area, which is densely populated with beam line components, shielding walls, cable trays, tubes and other equipment. In particular, the beam line passes to a large extend through an area, which is occupied by a shielding wall. Consequently, this shielding wall has to be modified, but its shielding functionality and its stability has to be maintained. Therefore, the actual situation of the relevant area has been recorded by a 3D laser scan. The gathered information has been added to a 3D model as first step. Then the new beam line has been modelled and potential collisions have been identified. In parallel radiation shielding simulations using FLUKA have been carried out to investigate possible options to shield the radiation generated by the beam. Furthermore, a structural analysis has been performed by an external contractor to study the feasibility of releasing load on the central shielding wall, which has to be modified for the new HHD beam line. These studies showed – on the level of detail investigated so far – no showstopper, but further shielding and civil engineering measures are required to ensure the radiation shielding and the structural stability of the walls. As a next step, a detailed design of the modified wall accompanied with a more detailed structural analysis is planned.

The integration and redesign of shielding walls should be completed by mid-2021. A procurement period was foreseen in 2022, followed by installation and commissioning in 2023. It was planned that the beam line becomes operational by end of 2023. However, shortly before this report has been written, the project has been de-prioritized due to financial constraints of the GSI budget of the coming years.

References

- [1] Sapinski, M.; et al.: Proposal and conceptual design of new HHD dump line. Internal document, GSI, 2019

13.5 Operation Infrastructure Support

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

In 2020 a variety of support activities have been carried out by the Operation Infrastructure Support OIS, i.e. by the departments of technology laboratory and mechanics & metalworking. Both departments continued their strong collaboration e.g. of using special welding and galvanic Cu plating technologies especially for the 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 2020 and in preparation of the beam time 2021.

Highlights

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

Production of further parts for the First of series for Alvarez Upgrade, e.g. half drift tubes, plunger, seals for stems, and coupling loops.

Figure 95. Mounting of the 13 m long Laser beam pipe at FAIR SIS 100 construction site. – mid: Large demo tank for Alvarez tank during Cu plating. – right: The tank directly after Cu plating.

A very challenging project with respect to handling was the construction of a 13 m long Laser beam pipe for SIS100 that meanwhile has been mounted on the FAIR construction site.

- After testing the feasibility for cutting and welding of flanges of prototype SIS100 magnetic dipole beam pipe vacuum chambers in 2019 the series procedure has been started in 2020 incl. the required precision control measurements.
- The series of 3000 CuBe strips for the stochastic cooling devices for FAIR have been shaped by tempering in our vacuum oven.
- FEM analysis support for SIS100 and HEBT as well as String Test vacuum chambers, and for SIS100 magnets.
- Important milestones have been reached in the galvanic workshop. After high-effort preparative works especially for the anode setup the large scale Alvarez demo and the first of series FOS tank have been successfully Cu plated. For the demo a detailed study of the lateral Cu-layer thickness distribution has been performed to fix the parameters for the FOS and for the later series plating.

In parallel to the technical support of the different projects the galvanic retrofitting has made significant progress. Both requests for building and operation permission have been submitted, and the detailed design phase is ongoing. Start of construction work is planned in late summer 2021.

13.6 Contribution to the FAIR Project

13.6.1 Commissioning of p-Linac ion source at CEA/Saclay

Authors: R. Berezov, J. Fils, R. Hollinger, K. Knie, C. Kleffner, O. Delferriere (CEA/Saclay), Y. Gauthier, O. Tuske (CEA/Saclay)

The p-Linac ion source will serve as an injector into the proton linac to provide primary proton beams for the production of antiprotons. The pulsed ion source, developed and built in CEA/Saclay operates with a frequency of 2.45 GHz based on an electron cyclotron resonance plasma production. The compact Low Energy Beam Transport (LEBT) consists of two solenoids including two integrated magnetic steerers to adjust the horizontal and vertical beam position. Behind the LEBT, an electrostatic chopper is mounted in front of the RFQ to shorten the beam pulse to 36 µs.

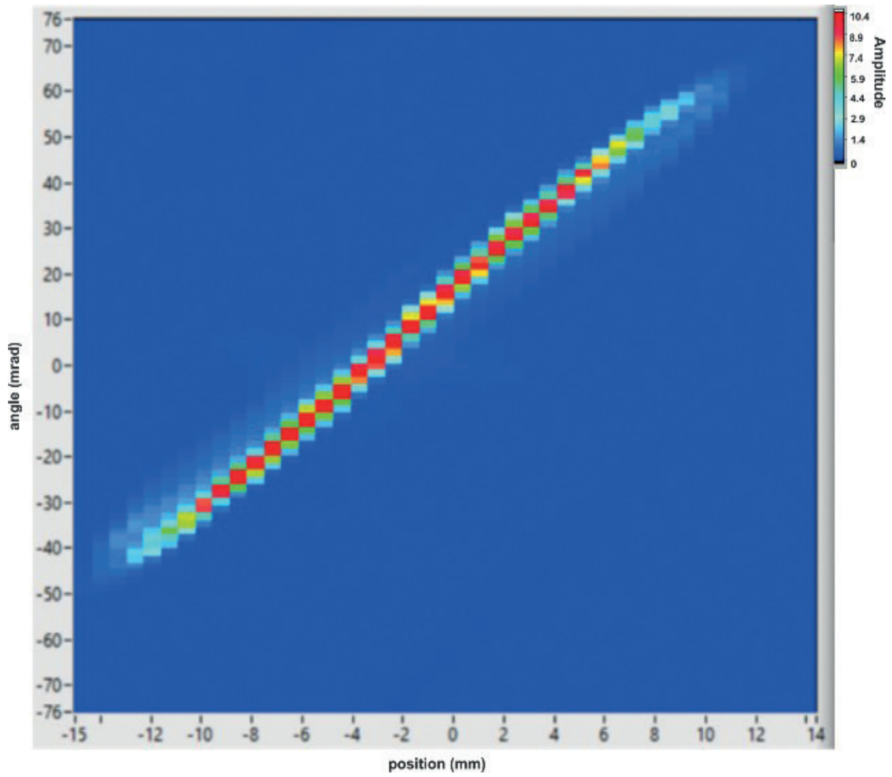

Figure 96. Emittance measurement behind the chopper cone.

The factory acceptance test of the proton injector was successfully accepted in 2020. The main specified parameters are in a good agreement with the specifications and presented in Table 4. The intensity of the proton beam is higher than 100 mA and was measured with the Faraday cup at the end of the LEBT behind the chopper cone. The proton fraction is higher than 80 % and was observed with a Wien filter (mass separator to analyse the ion species) in a diagnostic chamber between the solenoids. The availability of the ion source operation was checked during a long time test run lasting several weeks. The measured normalized rms emittance (95%) behind the chopper cone performed with Alison scanner (emittance measurement unit) according to the specifications is smaller than 0.3π mm mrad and presented in the Figure 96. During the commissioning at CEA/Saclay the measurement of the intensity transmission map through the chopper conus as a function of both solenoid values was done. The measured emittance in this area as a function of different solenoids parameters provides the twiss parameter and allows therefore the best fit to the RFQ acceptance.

Main parameters	required	achieved
Beam Intensity	≥100 mA	≥100 mA
Beam Energy	95 keV	95 keV
Proton fraction	>80 %	80-85 %
Beam emittance, pi.mm.mrad	<0.33	0.25-0.3
Availability	≥ 95 %	≥ 95 %

Table 4. The main parameters of the proton injector.

After dismounting at CEA/Saclay, the proton injector was transported to the storage place in Weiterstadt (Darmstadt) end of 2020. After construction of the new proton linac building, the proton injector will be built up again for site acceptance test. The commissioning of the proton injector at GSI will be done in several phases. In the first step, the measurements of emittance, extracted current and beam composition behind ion source will be performed, including operation with a new control system, provided by GSI. In the next step the measurements to characterize the beam performance will be carried out in the LEBT, between the solenoids inside diagnostic chamber and behind the second solenoid. In the last phase of the commissioning the installation of the chopper with new fabricated injection cone for RFQ will be done. The beam intensity and emittance will be measured behind the injection cone. After the site acceptance test, the proton injector will produce proton beam for further commissioning and operation of the proton linac.

Reference

- [1] Berezov, R; et al.: Review of Scientific Instruments / 90, 123309 (2019) DOI: 10.1063/1.5127820

13.6.2 Contribution to p-Linac RF

Authors: A. Schnase, G. Schreiber, S. Pütz, E. Plechov

Work at the p-Linac test stand

In 2020 the remaining Thales Klystron #8 was delivered. There were still issues with the operation characteristics of the Klystron ion pumps, where not all pumps started, when the pressure rises. Thales recommends to either increase the ion pump voltage for some minutes from 5 to 7 kV, or to use a hammer to hit the pump. We find out that keeping the ion pumps active at 5 kV without interruption while recording the ion pump current in 15 min intervals is helpful. At the end of 2020 we reached the situation that all 16 ion pumps of all eight klystrons were running. Still we have the remaining problem that the in total 17 ion pump power supplies provided by Thales do not fulfill the interlock conditions required.

The water-cooled high power load #9, which was used at Thales for nine Klystron factory tests was returned to us. The S-Parameter S_{11} was checked with cooling water in the temperature range from 25 to 35 °C. This shows that the load is still within specifications. It will be put to FAIR storage.

We characterized another set of WR2300 size E-Bends, H-Bends, and also flexible waveguides from three companies. Thus we are prepared for the p-Linac waveguide ordering process to find a good balance between quality and price.

The work for the HV klystron modulators is progressing. Two pulse transformers were delivered, and the commissioning of the first prototype system is proceeding.

We modified the operation temperature of the existing high power circulator from 25°C to 29°C to match the p-Linac cooling water specifications (see Figure 97). In several steps, the outer magnetic field was modified by shims, and then the cooling water temperature was slowly adjusted to make sure that the temperature level is stable. One modification step takes approximately half a day. This experience will be helpful when ordering the next high power circulators for the p-Linac klystron systems.

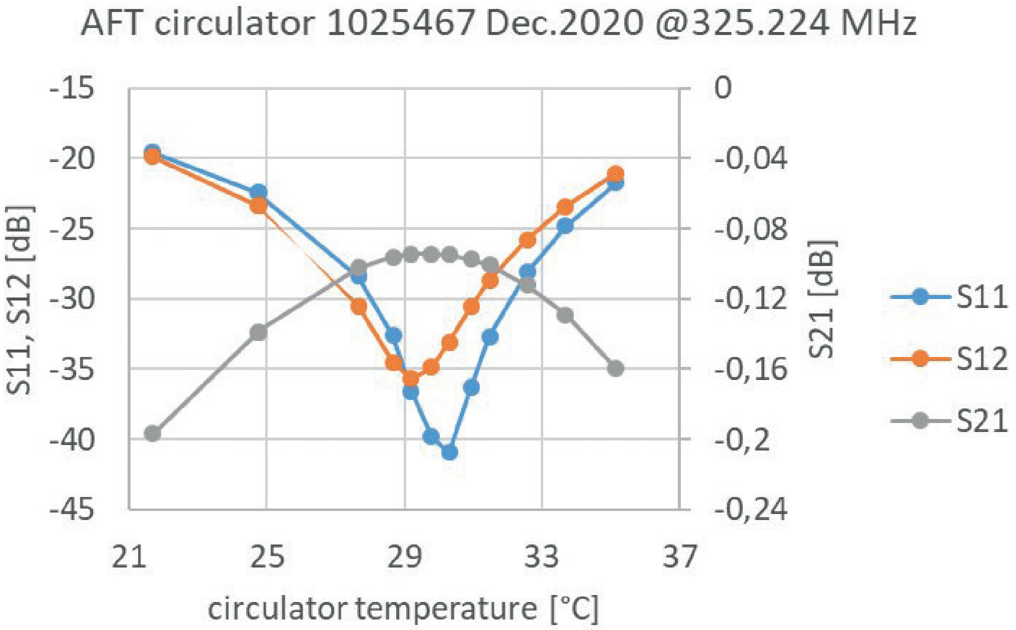

Figure 97. LRF7.2-1: S21 of circulator modified for p-Linac cooling water temperature.

In this context, we also helped the p-Linac group to upgrade the cooling system in the concrete shielded area, where the p-Linac cavities and the RFQ are planned to be tested.

Outlook for 2021

We intend to provide high power rf pulses with the TH2181 klystron within 2021 to perform high power component tests. Due to delays of the p-Linac schedule, the process for ordering the remaining seven high power circulators is postponed for 2nd half of 2021 or later.

13.6.3 Development of Stochastic Cooling System for CR

C. Dimopoulou, A. Bardonner, R. Böhm, M. Bräscher, O. Gorda, R. Hettrich, J. Krieg, C. Peschke, S. Wunderlich, C. Zhang, R. Stassen (FZJ), B. Breitkreutz (FZJ)

The 1-2 GHz stochastic cooling system of the Collector Ring (CR) will provide 3D cooling of hot secondary beams, max. 10^8 ions (antiprotons @ v = 0.97 c, rare isotopes @ v = 0.83 c), from production targets. The CR stochastic cooling system mainly consists of two cryogenic plunging Pick-Ups (PU), one Palmer PU, and two kickers. Some highlights for the R&D progress in 2020 are reported as follows:

Pick-Ups

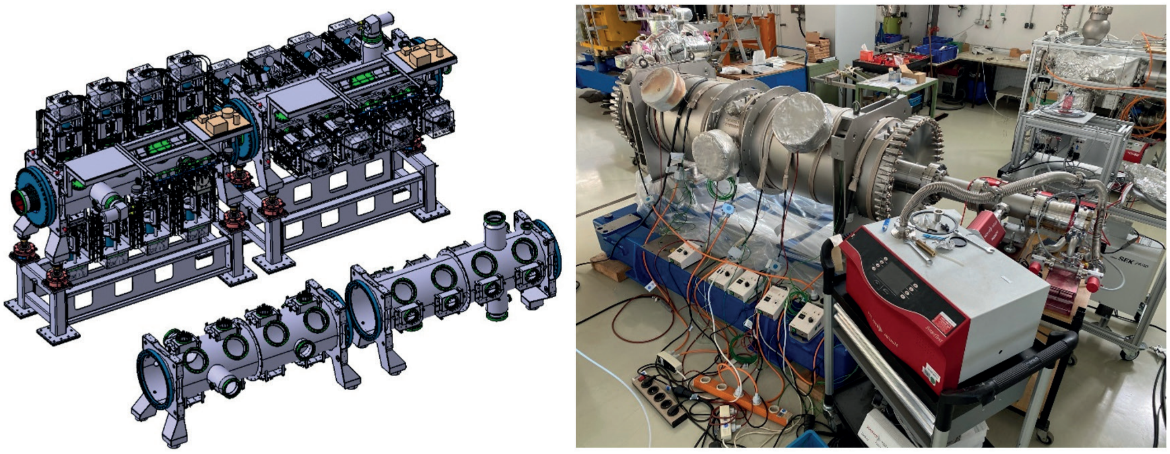

Figure 98. Cryogenic plunging PU tanks (left) and Palmer PU (right) (Design by R. Böhm).

The two vacuum tanks for the cryogenic plunging PUs (see Figure 98 left) have been ordered. All 16 linear motor drive units are ready assembled and stored. For about 3000 Ag/CuBe plunging foils, the thermal treatment of the CuBe foils in vacuum oven at GSI technoloy laboratory and the procurement of their Cu-holders have been done. The re-design of the slotline electrode modules for simplicity and feasibility has been finished; preseries of the metallised ceramic electrodes & combiner boards have been ordered.

The Palmer PU with Faltin rail electrodes (see the right photograph in Figure 98) will be used for precooling of RIBs. It has been assembled at ZEA-1 (FZ Jülich) in summer 2020 and is already installed at COSY for testing with 0.83 c protons in 2021.

Kickers

The kickers will use FZJ-designed, HESR-like slot-ring electrodes with the proper impedance in 1-2 GHz. The preliminary engineering design is shown in Figure 98, where the two tanks are for transverse and longitudinal cooling, respectively. This new concept is being integrated in the overall CR stochastic cooling rf-signal scheme and in the CR building.

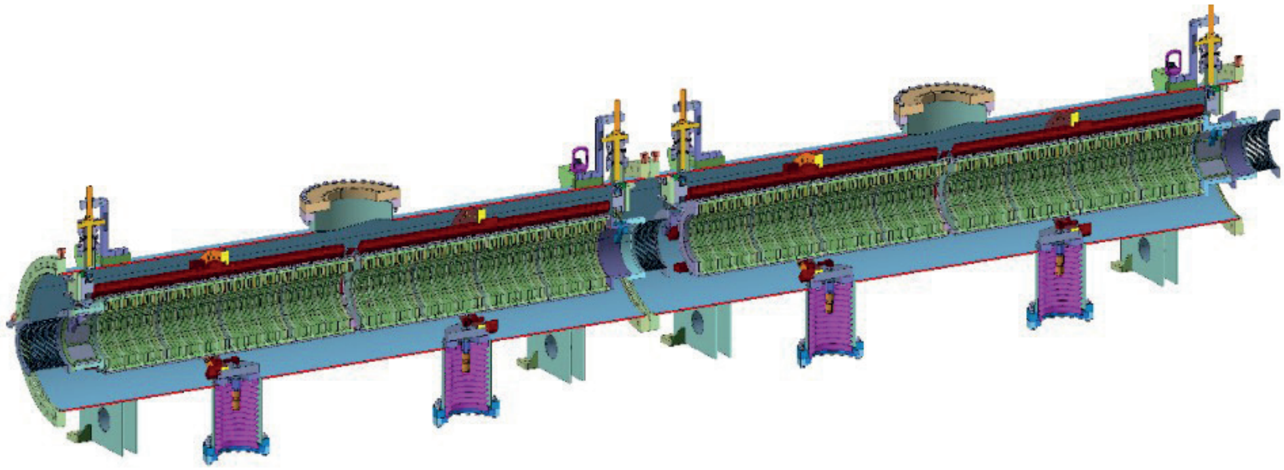

Figure 99. Preliminary engineering design of the kickers (Design by R. Greven, ZEA-1, FZJ).

RF Signal processing components

The series of the low noise preamplifiers (with noise figure ≤0.6 dB in 1-2 GHz) for all the PUs have been ordered, delivered to GSI and passed the Site Acceptance Test (SAT). The series of 34 highly linear power amplifiers (250 W; 1-2 GHz) for the kickers have been delivered to GSI. SAT is ongoing at GSI, on two dedicated test benches. By now, 8 of them have passed the SAT.

Microwave-Damping Tubes

All 13000 microwave-damping ceramic tubes for the series have been procured. Then, they were resistively coated by NiCr sputtering. Their UHV tests gave acceptable results. We are expecting the prototype quadrupole/sextupole vacuum chamber from BINP to test the mechanics concept (assembly holders) for the tubes in late 2021.

14. Annex

All publications of the GSI in the year 2020 and all publications related to GSI's large scale research facilities are listed in the publications database (VDB) at the GSI repository: <http://repository.gsi.de/collection/VDB?ln=en>.

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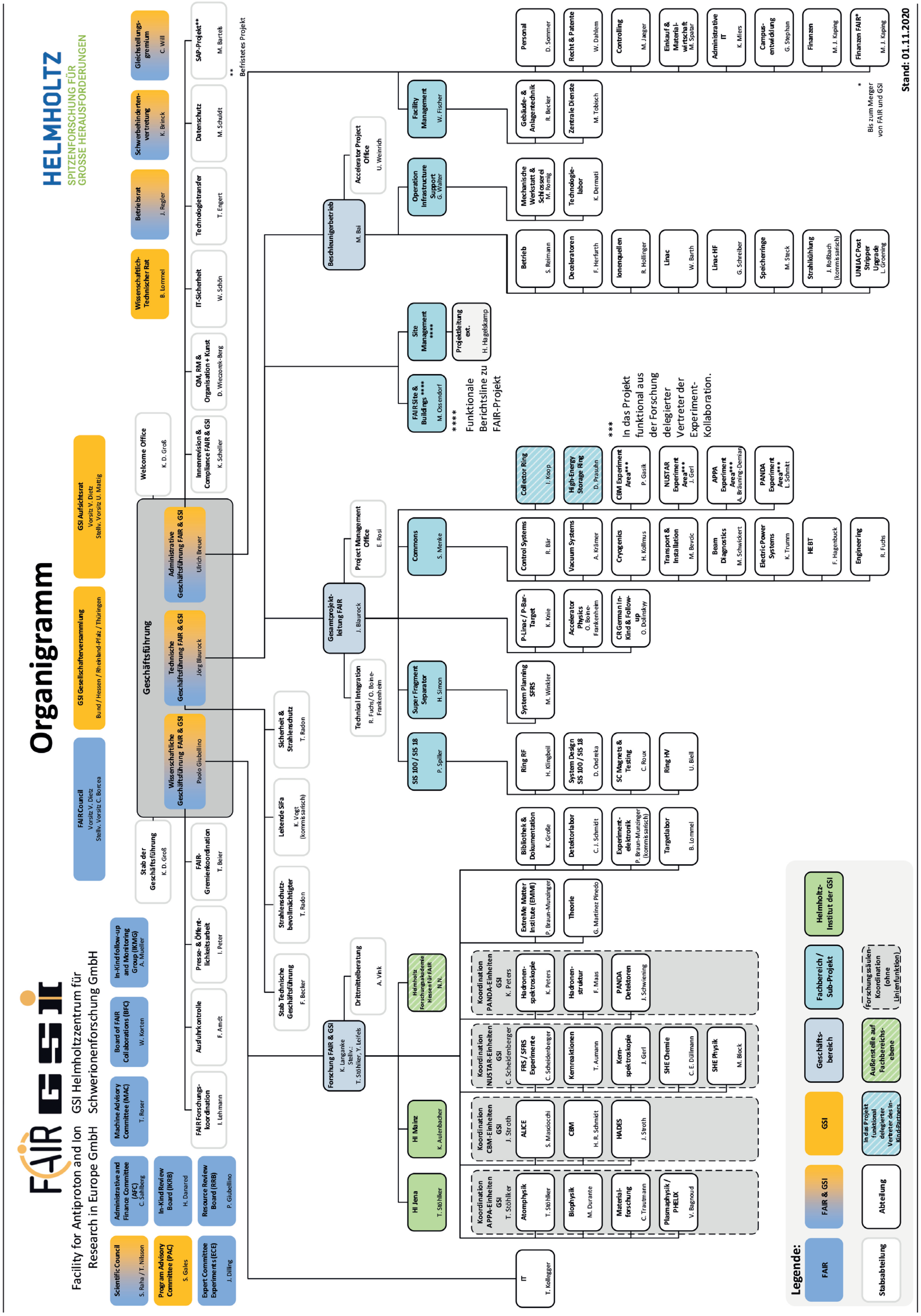
14.2 Organisational chart



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. The research activities About 95% of GSI are in the research field of matter and about 5% in the field Health/Cancer Research. 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.