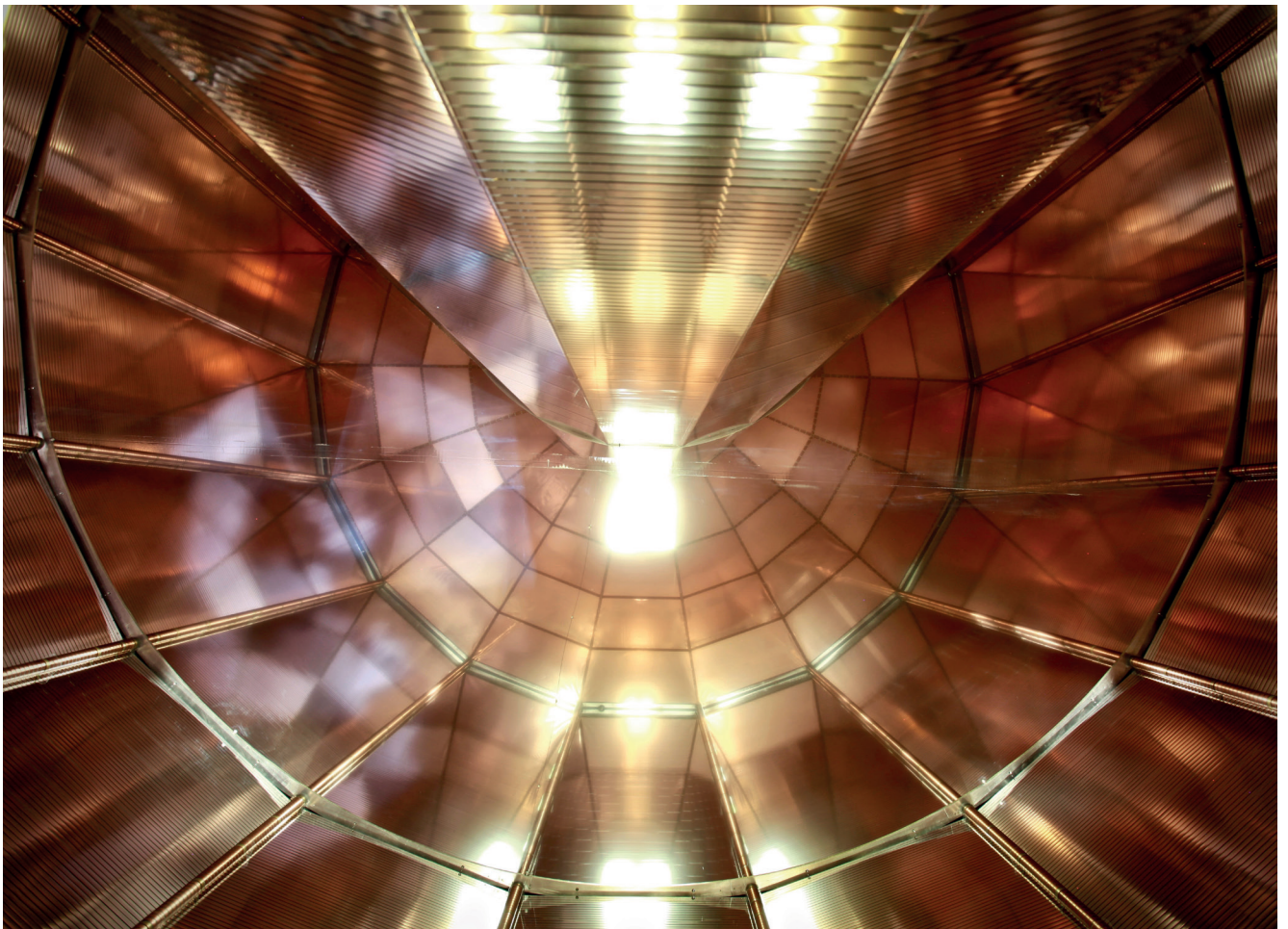


GSi REPORT 2020-1

# GSi-FAIR SCIENTIFIC REPORT 2019

An overview of the 2019 achievements in science and technology



## Cover

The ALICE experiment at CERN's Large Hadron Collider (LHC) in Geneva, Switzerland, is undergoing major upgrades to profit fully from the much increased heavy-ion collision rate of 50 kHz, which will be delivered by the LHC from 2021 onward. In order to achieve continuous readout for the heart of the ALICE tracking system, i.e. the Time Projection Chamber (TPC), the detector chambers and readout systems are replaced. The multi-wire proportional chambers, delivering an outstanding performance of the TPC in the first decade of ALICE operation, were replaced with new chambers based on Gas Electron Multiplier (GEM) technology. A significant fraction of these large-area GEM chambers was built in 2017-18 at GSI and installed in the TPC until September 2019, in collaboration between the local ALICE team and the GSI detector laboratory. The photo above was taken from the location of the final chamber before its insertion. The image of GEM foils is reflected by the TPC's central electrode, separating the sensitive volume of 90 cubic meters into two halves. The TPC is back in operation since November 2019 for commissioning with laser and cosmic rays. It will return to its position at the heart of ALICE by the end of 2020, getting ready for the next LHC run.

Photograph by Piotr Gasik/GSI, text by Silvia Masciocchi/GSI

# **GSI-FAIR SCIENTIFIC REPORT 2019**

An overview of the 2019 achievements in science and technology

## Imprint

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# 1. Executive summary of the research at GSI & FAIR

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

2019 was a very busy year: the evaluation of the FAIR project in spring 2019, the beam time period from February 19<sup>th</sup> to April 15<sup>th</sup>, the preparation of the documents for the strategic evaluation of the GSI proposals to the research field Matter within the Helmholtz association during summer, and finally in November and December an engineering run for the accelerators and experiments.

In 2015, the shareholders of FAIR GmbH had decided to reassess the FAIR project in spring 2019. This review by an international expert committee chaired by Prof. Lyn Evans, CERN, took place in several meetings between November 2018 and April 2019. In its final report, the expert committee confirmed FAIR's globally outstanding scientific programme. The report also attests to the FAIR project and the campus with the powerful and efficient organizational structures and processes that the management has established and implemented over the past years.

In the Civil Engineering division responsible for the construction of the FAIR facilities, the remaining excavation work for the SIS100 tunnel and the CBM building as well as the construction work for the SIS100 tunnel and the intersection structure, consisting of the transfer building, sections of the transfer tunnel and the main supply building, in the construction area North made good progress. For the accelerator area, significant successes can be recorded, such as the delivery of more than 90 (out of a total of 110) SIS100 dipoles of the first of two HESR injection septums to Jülich, the signing of the cooperation agreement for the cold testing of more than 80 SIS100 quadrupole modules at the NAFASSY test facility in Salerno (Italy) or the delivery of the first 8 power amplifiers for the stochastic CR cooling system to GSI.

In the planning and preparation of the FAIR experiments, the collaborations are initially concentrating on the day-one launch configurations, which can be realized with existing financing for the most part. The launch configurations will allow the outstanding FAIR experiment programme to get off to a swift start as soon as the first beams are available in the new facility complex.

In February 2019, the measurement campaign, which had been postponed from 2018, started on schedule and was very successful. Numerous detectors and instruments developed and built for FAIR were used. Particularly noteworthy are experiments on NUSTAR's R<sup>3</sup>B setup using the superconducting GLAD magnet and on HADES, where newly developed detector components and read-out processes were used for CBM and PANDA. In addition, the Cryring was put into operation - a Swedish in-kind contribution to FAIR, which was set up in the GSI target hall. In addition, numerous other experiments in nuclear physics including heavy element research, atomic and plasma physics as well as materials research, space research and biophysics with ion beams were addressed.

After the scientific review of GSI and its Helmholtz institutes in November 2017, the strategic evaluation of the Research Field Matter and the POF IV proposals of the three programmes took place in January 2020. For this purpose, the programme proposals were written in 2019. GSI has returned to the procedure for the coming funding period with the Darmstadt campus, while activities of the Darmstadt campus concerning the construction, installation and commissioning of FAIR accelerators and detectors remain excluded from the regulatory procedure. The activities of the Department of Biophysics were moved from the Research Field Health (Cancer Research Program) to the Research Field Matter (Program Matter, Materials and Life). GSI is contributing exclusively in the Research Field Matter during the next funding period. In addition to own research activities, denoted LK I in the POF terminology, the LK II user operation during FAIR Phase-0 was also included in the POF procedure again.

In the strategic evaluation, the program topics within the three programs of Matter, Matter and Universe MU, Matter, Materials and Life MML, and Matter and Technology MT, in which GSI is involved, were rated "Outstanding" to "Excellent" and received the recommendation of financial

growth A and B. Only the topic “Cosmic Matter in the Laboratory (CML)” in MU was assessed as “Very Good” in the category “Impact and Risks” due to the risk of possible delays in the construction of FAIR, with a financial recommendation C (no financial growth). The recommendations of the expert group emphasize the importance of the FAIR Phase-0 program as a transition from GSI to FAIR and the urgency to prevent a delayed start of FAIR.

Finally, the year was concluded with an engineering run from November 11<sup>th</sup> to December 20<sup>th</sup>.

Outcome of the beam times, recent developments and scientific achievements are reported in the following contributions.

In addition it is worth to mention, that a Welcome Office for GSI/FAIR was established on the Darmstadt campus for scientific guests and users of the facilities. The Welcome Office acts as an interface between guests and different departments and is the contact point for different questions and concerns of the guests. Already in the run-up to a visit the guests register there which initiates various processes in the building. Necessary formalities such as invitation letters or guest contracts are taken care of and the guests can carry out the obligatory general safety instruction online in advance so that they can start their work as soon as possible after their arrival.

## Beamtime in 2019

Coordinator: Dr. Daniel Severin

experiment proposal number	spokesperson	large scale facility and target station	experiment topic	main shifts	parasitic shifts
S471	Herrmann, Norbert	SIS18 HTD	mCBM @ SIS18 - A CBM full system test-setup for high-rate nucleus-nucleus collisions at GSI / FAIR		37
S477	Stroth, Joachim	SIS18 HAD	Properties of hadron resonances and baryon rich matter	88	
S444	Gernhäuser, Roman	SIS18 HTC	R3B - 2018 Commissioning (CALIFA, L3T, GLAD, NeuLAND & Tracking)	4	7
S465	Aumann, Thomas	SIS18 HTC	Dipole response of the drip-line nuclei ${}^6\text{He}$ and ${}^{22,24}\text{O}$	9	
S454	Heil, Michael	SIS18 HTC	Studying the astrophysical reaction rate of ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ via Coulomb dissociation of ${}^{16}\text{O}$ into ${}^4\text{He}$ and ${}^{12}\text{C}$	15	
U308	Yakushev, Alexander	UNILAC X8	First chemical study of element 113 behind TASCA		23
U310	Rudolph, Dirk	UNILAC X8	Spectroscopy of Flerovium Decay Chains & Discovery of ${}^{290}\text{Fl}$	22	12
U313	Laatiaoui, Mustapha	UNILAC Y7	Laser spectroscopy of nobelium and lawrencium	30	
U314	Raeder, Sebastian	UNILAC Y7	High-resolution laser spectroscopy of nobelium isotopes and isomers		16
UBIO	Friedrich, Thomas	UNILAC X6	Biophysics research	6	7
SBIO	Graeff, Christian Scholz, Michael	SIS18 HTA/ HTM	Biophysics research	16,8	
ESA	Weber, Uli	SIS18 HTA/ HTM	ESA research	8,4	
UMAT	Trautmann, Christina	UNILAC M1/ M3/X0	Materials research	56	118
U317	Rosmej, Olga N.	UNILAC Z7	X-ray mapping of the heavy ion beam intensity distribution and the ion beam energy loss in the plasma physics experiments at FAIR		10
U318	Christakov, Konstantin	UNILAC Z7	Investigation of charge state and energy loss of heavy ions after interaction with inductively coupled plasma		10
E129	Rothardt, Jan	CRYRING	Photoionization of $\text{C}^+$ ions at CRYRING	10	

Table 1. Beamtime in 2019



## 2. Research of the APPA departments

Coordination: Prof. Dr. Thomas Stöhlker, GSI/Helmholtz-Institut Jena

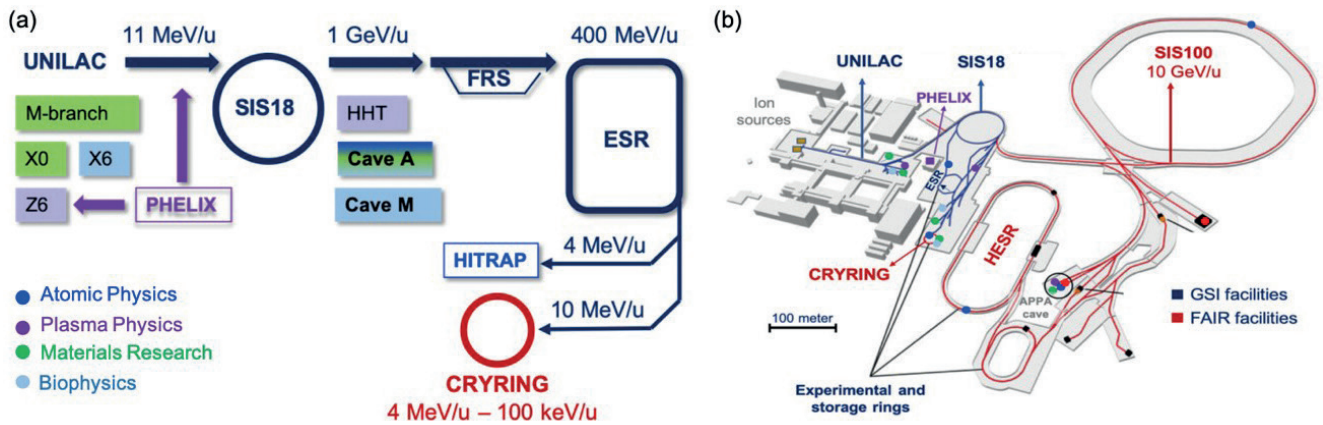


Figure 1. (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (Th. Stöhlker et al., Nucl. Instr. Meth. B 365, 680 (2015)).

At GSI, the research departments Atomic Physics, Biophysics, Plasma Physics, and Materials Research are organized under the roof of APPA/MML, where MML is the Helmholtz program “From Matter to Materials and Life”, and APPA, “Atomic, Plasma Physics and Application”, is one of the four research pillars of FAIR. With the intense ion beams, GSI and 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. In Figure 1, 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  
 Author: Z. Andelkovic, A. Bräuning-Demian, R. Grisenti, J. Glorius, A. Gumberidze, F. Herfurth, W. Quint, Y. Litvinov, R. Sánchez, U. Spillmann, S. Trotsenko and T. Stöhlker



Figure 2. From September 9<sup>th</sup> to 13<sup>th</sup>, the SPARC Collaboration held its 16<sup>th</sup> Topical Workshop and Collaboration Meeting at the Friedrich-Schiller University Jena and the Helmholtz-Institut Jena. The particular focus was on the very first experiments scheduled for FAIR Phase-0 at ESR and CRYRING@ESR.

In close cooperation with scientists all over the world within the SPARC collaboration which is 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: 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 at FAIR, the energy range will be further extended to highly relativistic energies ( $\gamma$ -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 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, lasers, x- and  $\gamma$ -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 2019, emphasis was given to the preparation of 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). These experiments are scheduled 2019/2020 within the framework of FAIR Phase-0 with the particular challenge to commission the rings along with the new FAIR control system to be applied for the first time for ring operation. The preparation of these experiments was the central point of discussion of the 16<sup>th</sup> topical SPARC workshop (s. Figure 2).

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-Institut 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 2019

### Experiments at HITRAP / TRAPS

#### He-like boron ions $B^{3+}$ studies at SPECTRAP/HITRAP

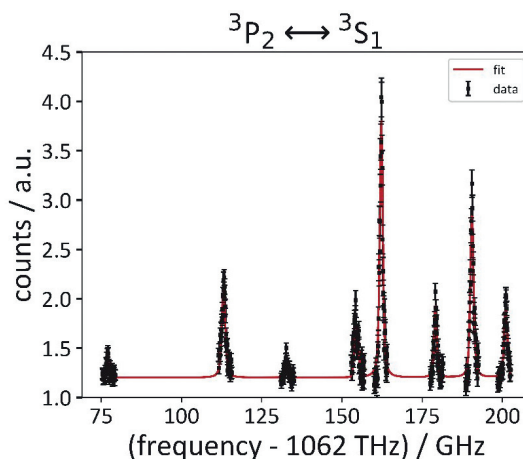


Figure 3. Hyperfine spectrum of He-like  $^{11}B^{3+}$ .

Laser spectroscopy measurements on He-like boron ions  $B^{3+}$  were performed at the HITRAP facility, using the local electron beam ion source (EBIS) and the beam line leading to the SPECTRAP experiment. The prototype version of the CRYRING@ESR fluorescence detector was installed on top of the SPECTRAP magnet. The detector was designed as a general-purpose detector for collinear and anti-collinear laser spectroscopy experiments at CRYRING@ESR and is able to detect fluorescence photons emitted at 280 nm by the He-like boron ions. Together with a frequency-doubled continuous wave laser system also employed at CRYRING@ESR, the setup enables high precision measurements of the hyperfine structure in the  $1s2s\ ^3S_1 - 1s2p\ ^3P_{0,1,2}$  transitions. Uncertainties in the ion's accelerator voltage and thus in the ions velocity were reduced by combining collinear and anti-collinear measurements of one component of which the transition frequency is extracted. By employing the Doppler-shift of the frequency of the light wave in the moving frame of the ion, the velocity of the ion and, hence, the acceleration voltage can be determined with high precision. Figure 3 shows a typical resonance recorded during the experiment. The analysis is presently ongoing (A. Buß et al. to be published).

#### S-EBIT for high-precision experiments with magnetic micro-calorimeters

An Electron beam ion trap (S-EBIT), provided by the Stockholm University for the Helmholtz Institute Jena, enables to produce highly-charged ions in rest in the laboratory. The S-EBIT is currently in operation at GSI and serves as a test facility for advanced instrumentation developed by the SPARC collaboration in particular for the realm of a high-precision x-ray spectroscopy (few keV region of interest). Here, the application of the x-ray optics developed at the HI-Jena is of particular interest for optimizing the measurement efficiency in a broad range of x-ray spectroscopic studies. In the current study, the maXs-30 magnetic micro-calorimeter (MMC) has been set up at the EBIT in

combination with a data acquisition system based on novel data processing algorithms. The MMC has an active detector area of  $4 \text{ mm}^2$  divided into  $8 \times 8$  pixels and the spectral resolution around 20 eV (FWHM). The EBIT was operated with a 10 keV electron beam and a current of 25 mA. A gaseous Fe-compound and the electron cathode material were used as the sources of iron and barium. The experimental setup can be seen in Figure 4 (left). As an example, Figure 4 (right) shows the x-ray spectrum obtained by preliminary analysis. The L x-ray transitions of highly charged barium are indicated (S. Trotsenko et al. to be published).

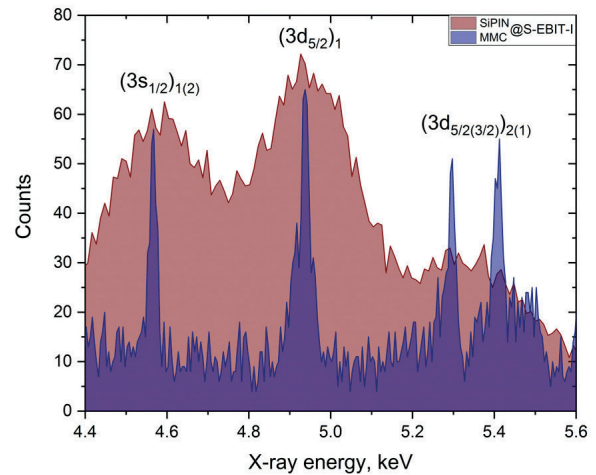
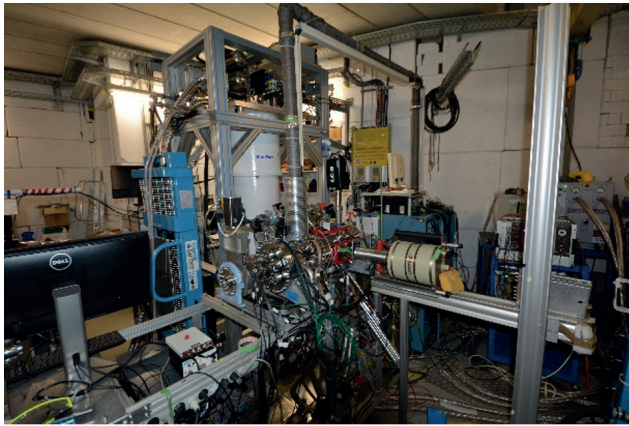


Figure 4. (Left): The experimental setup at the S-EBIT in the X4 cave at GSI. (Right): High resolution X-ray spectrum of barium ions recorded by the maX-30 MMC.

## Experiments at CRYRING

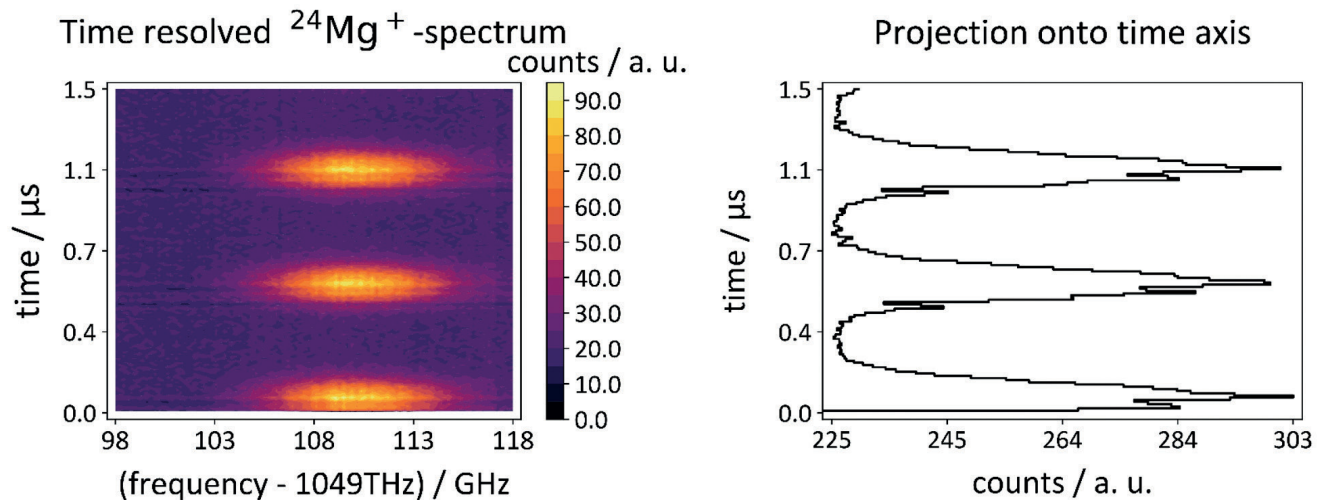
Laser spectroscopy on  $^{24}\text{Mg}^+$ 

Figure 5. Example of the  $\text{Mg}^+$  resonance recorded at CRYRING@ESR. In resonance, also the bunch structure of the stored ions becomes visible. Left: number of detected photon events (color coded) as a function of time (y-axis) and laser frequency. The bunch structure is clearly visible along the vertical axis and the individual bunches appear as peaks in the projection onto the time axis (right).

Laser spectroscopy on  $^{24}\text{Mg}^+$  was carried out at CRYRING@ESR during the engineering run in spring 2019. Ions from the local ion source were accelerated and stored at 170 keV/u with a lifetime of around 10 seconds. The laser light at 285 nm driving the  $3^2\text{S}_{1/2} - 2^3\text{P}_{1/2}$  transition in  $^{24}\text{Mg}^+$  was produced by a frequency doubled continuous wave dye laser, while the fluorescence was collected by UV-photomultipliers using the general-purpose detector developed at the University of Münster. The FPGA-based data acquisition system for single photon tagging originally developed for the NUSTAR/LaSpec experiment was adapted for this task. Figure 4 shows the resonance recorded during the experiment (K. Mohr et al. to be published).

Photoionization studies of  $\text{C}^+$  ions

At CRYRING@ESR the very first experiment has been started with particular focus on photoionization studies of  $\text{C}^+$  ions (J. Rothhard et al., E129), provided by a local ion source directly coupled to CRYRING@ESR. Photoionization plays a dominant role where matter (cosmic or earthbound) is in the plasma state. Precise knowledge of the corresponding photoionization cross sections is a prerequisite for accurate modeling of plasma dynamics. For this purpose, a portable XUV source has been coupled to the CRYRING@ESR whereby the vacua of CRYRING@ESR and the XUV source are coupled by a windowless differential pumping station. Note, this experiment is at the same time a precursor experiment for future experiments at the HESR storage ring.

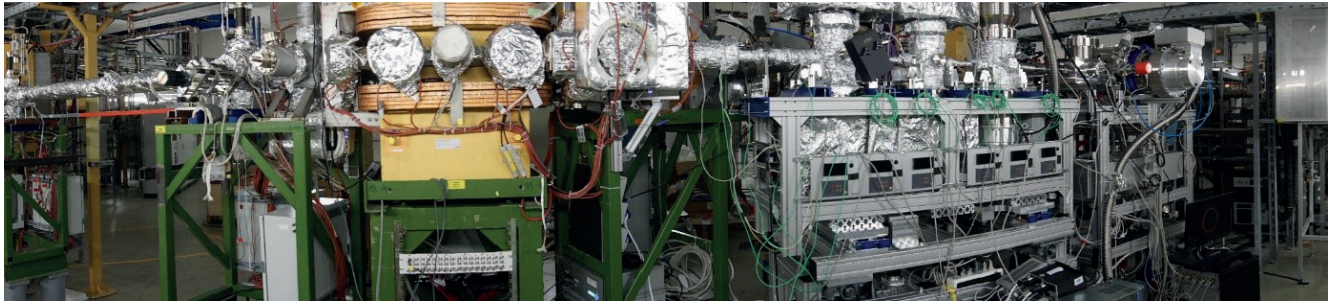


Figure 6. Portable, intense laser-based XUV photon source (right side) coupled to CRYRING@ESR (left side) via a windowless, differential pumping station.

In Figure 6, the experimental setup installed at CRYRING@ESR is shown. Ions provided by a local ion sources have been injected into the CRYRING@ESR and accelerated to various beam energies (up to max. rigidity of the ring). At these energies, coincidences between the laser pulses and up-charged  $C^{2+}$  were recorded by a moveable particle detector, mounted in the dipole section behind the photon/ion beam interaction zone. In 2019, 10 of 30 shifts of beam time have been provided and the experiment will continue in 2020/2021 (V. Hilbert et al., to be published).

## Experiments at ESR

Electron capture (EC) decay of hydrogen-like  $^{142}\text{Pm}^{60+}$

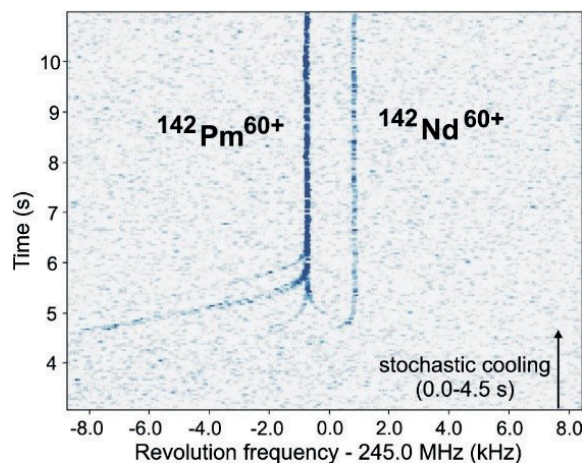


Figure 7. Example of the measured traces of stored  $^{142}\text{Pm}^{60+}$  and  $^{142}\text{Nd}^{60+}$  ions in the ESR (revolution frequency versus time after injection). More than six  $^{142}\text{Pm}^{60+}$  ions were stored in this example. Also, a single EC-decay daughter ion,  $^{142}\text{Nd}^{60+}$ , is present from the beginning in the plot.

A particularly important result is related to a new test of modulated electron-capture decay of hydrogen-like  $^{142}\text{Pm}$  ions: An experiment addressing electron capture (EC) decay of hydrogen-like  $^{142}\text{Pm}^{60+}$  ions has been conducted at the experimental storage ring (ESR) at GSI (see Figure 7). The decay appears to be purely exponential and no modulations were observed. Decay times for about 9000 individual EC decays have been measured by applying the single-ion decay spectroscopy method [1].

## Approaching the Gamow Window with Stored Ions

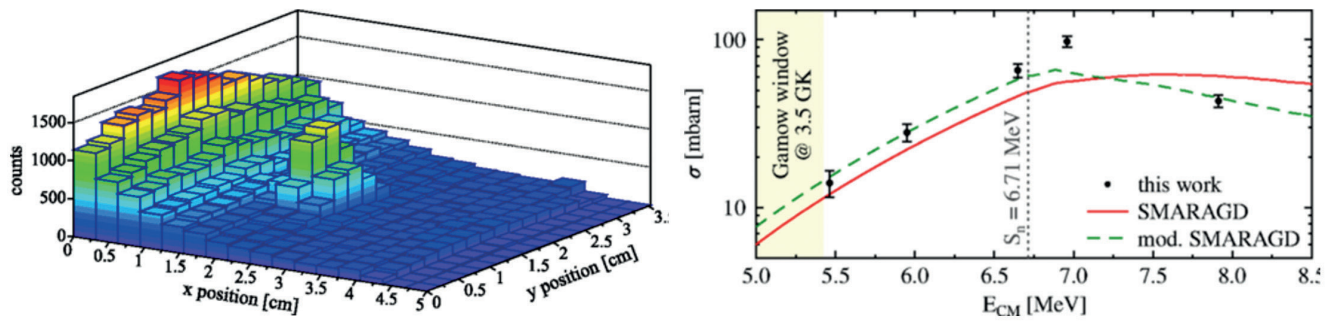


Figure 8. (Left) The ion hit distribution measured with a double-sided silicon strip detector DSSD is shown. On top of a broad background of elastically scattered  $^{124}\text{Xe}^{54+}$  ions a narrow cluster of  $^{125}\text{Cs}$  ions can be identified as products of the  $(p, \gamma)$  reaction. (Right) Comparison of experimental (black dots) and predicted cross sections: the red solid line shows the predictions obtained with the same input as used in the reaction rate databases for astrophysics. The dashed green line shows a similar calculation but changing the proton and neutron capture widths.

A very recent letter 'Approaching the Gamow Window with Stored Ions: Direct Measurement of  $^{124}\text{Xe}(p, \gamma)$  in the ESR Storage Ring' reports on the measurement of low-energy proton-capture cross-sections of  $^{124}\text{Xe}^{54+}$  in the heavy ion storage ring ESR (see Figure 8). The experimental data is presented on the left side of Figure 8, where the hit distribution of  $^{125}\text{Cs}$  ions measured by a double sided silicon strip detector DSSD is shown. For the first time it could be demonstrated that this experimental method enables reaction measurements inside the astrophysical important Gamow window (indicated as yellow shaded area in Figure 8 right). In combination with the rare ion beam facility at GSI/FAIR and deceleration capability of the ESR, this represents a powerful tool to improve our understanding of nuclear processes in explosive stellar scenarios such as supernovae or x-ray bursts. A broad international collaboration embedded into the SPARC collaboration under the lead of the ERC group ASTRUm and the atomic physics department performed these studies [2].

## Radiative electron capture as a tunable source of highly linearly polarized x rays

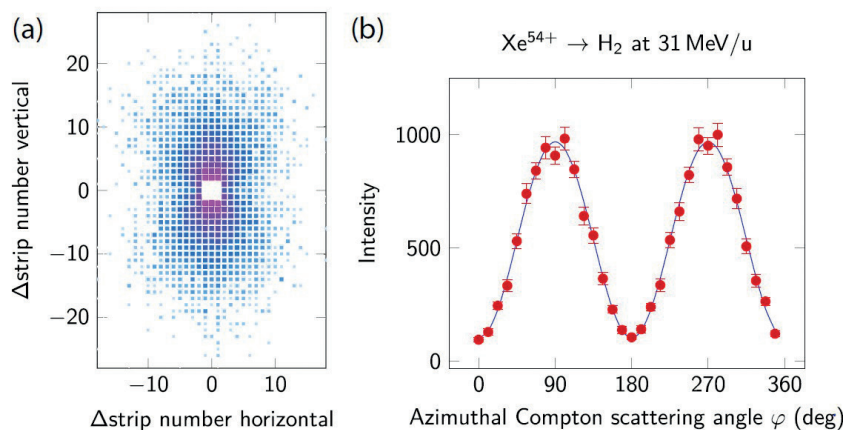


Figure 9. (a) Position distribution of the Compton scattered KREC photons with respect to the scattering position (0,0) in the polarimeter. Due to the high degree of linear polarization of the incident radiation, a clear anisotropy of the emission pattern is visible. (b) Azimuthal intensity distribution of the Compton scattered photons. The solid line is obtained by a least-squares adjustment of the Klein-Nishina formula and has been adapted to the partially polarized incident.

Radiative electron capture (REC) into the K shell of bare Xe ions colliding with a hydrogen gas target has been investigated. In this study, the degree of linear polarization of the K-REC radiation was measured and compared with rigorous relativistic calculations as well as with the previous

results recorded for  $U^{92+}$ . Owing to the improved detector technology (novel 3D polarimeter developed by the SPARC collaboration), a significant gain in precision of the present polarization measurement is achieved compared to the previously published results. The obtained data confirms that for medium-Z ions such as Xe, the REC process is a source of highly polarized x-rays (up to almost 100%; see Figure 9) which can easily be tuned with respect to the degree of linear polarization and the photon energy. We argue, in particular, that for relatively low energies the photons emitted under large emission angles are almost fully linear polarized [3].

### Relevance of Breit Interaction for electron-impact excitation of He-like uranium

The unique capabilities of the ESR storage ring for the investigation of ultra-fast atomic process involving high-Z ions have been exploited in a study of electron- and proton-impact excitation of Helium-like Uranium. This was done by using relativistic collisions of  $U^{90+}$  with hydrogen and argon atoms at the internal gas-jet of the ESR storage ring and by observing x-rays emitted following the decay of the excited states. The experimental data provide a first quantitative test of state-of-the-art theory for electron-impact excitation in the heaviest He-like ion and clearly demonstrate the importance of including the generalized Breit interaction in the treatment of the electron-impact excitation process [4].

### Experiments at CERN and DESY

#### g-Factor of lithiumlike silicon: new challenge to bound-state QED (AD at CERN)

The magnetic moment (g-factor) of lithium-like silicon ( $^{28}\text{Si}^{11+}$ ) has been measured by application of the continuous Stern-Gerlach effect on a single ion confined in a cryogenic Penning trap. The resulting value  $g = 2.000\,889\,888\,46\,(14)$  has an uncertainty 14 times smaller than the best previous measurement. At the same time, the theory value for this quantity  $g = 2.000\,889\,894\,4\,(34)$  has been calculated to an uncertainty two times smaller than previously, to the point where it is mostly determined by the unknown many-electron two-loop QED contributions. The obtained experimental value has a potential to validate the non-trivial parts of the many-electron two-loop QED contributions on a few percent level, and hence represents a stringent test of quantum electrodynamics in the presence of strong fields [5].

#### Crystal growth rates in supercooled atomic liquid mixtures (PETRA III at DESY)

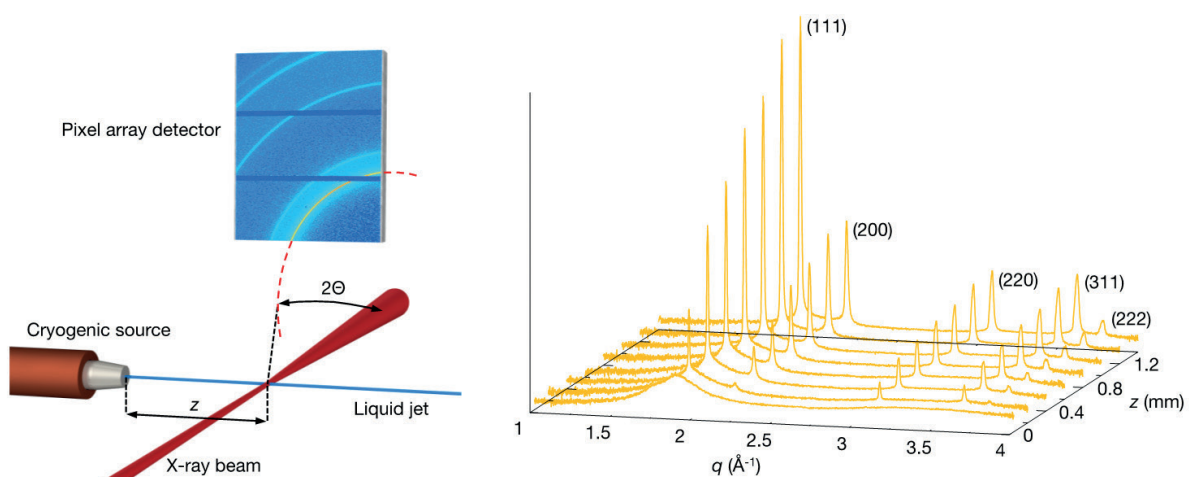


Figure 10. Schematic of the experiment and diffraction profiles. (Left part): Liquid jets with a uniform diameter of  $\approx 5\ \mu\text{m}$  were generated in a vacuum and probed with a 13 keV x-ray beam. The scattered x-rays were detected by a two-dimensional pixel array detector covering the  $10^\circ$  to  $40^\circ$   $2\theta$  diffraction angular range. Right part): Selection of area-normalized diffraction profiles from a jet (85% argon and 15% krypton) with as a function of the wavevector  $q$ .

Crystallization is one of the most fundamental phase transitions, but it still lacks a comprehensive theory at the microscopic level. The crystallization of binary mixtures is particularly important because of the great technological relevance of such systems. However, the observation of apparently different crystal growth regimes in binary liquids greatly puzzles our current understanding of crystallization. By combining x-ray diffraction from microscopic liquid jets with theoretical modeling and computer simulations, we have investigated the crystal growth rates in supercooled mixtures of argon and krypton, the simplest atomic binary liquids. Rare-gas liquids are particularly attractive model systems because crystal growth rates in these systems are predicted to be comparable to those found in pure metals. Our results establish the key role played by the thermodynamic complexity of binary liquid mixtures in the description of the kinetics of crystallization, providing a substantial step towards a more sophisticated theory of crystal growth [6].

## Theory

How to observe the vacuum decay in low-energy heavy-ion collisions?

In slow collisions of two bare nuclei with the total charge larger than the critical value  $Z_{cr} \approx 173$  the initially neutral vacuum can spontaneously decay into the charged vacuum and two positrons. In a recent theoretical study, it is shown that the vacuum decay can be observed via impact-parameter-sensitive measurements of pair-production probabilities at different collision energies. The possibility of such an observation is demonstrated using numerical calculations of pair production in low-energy collisions of heavy nuclei. The results reported will promote new efforts for the experimental detection of the vacuum decay in a supercritical Coulomb field. In particular, such experiments seem feasible with the CRYRING@ESR facility at GSI/FAIR, where storing of bare uranium nuclei at low energies is anticipated in the near future [7].

Ground-state hyperfine splitting of B-like ions in the high-Z region

The hyperfine splitting of the ground state of selected B-like ions within the range of nuclear charge numbers  $Z = 49-83$  is investigated in detail. The rigorous QED approach together with the large-scale configuration-interaction Dirac-Fock-Sturm method are employed for the evaluation of the interelectronic interaction contributions of first and higher orders in  $1/Z$ . The screened QED corrections are evaluated to all orders in  $\alpha Z$  by using an effective potential. The influence of nuclear magnetization distribution is taken into account within the single-particle nuclear model [8].

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- Ozturk, F. C. ; Akkus, B. ; Atanasov, D. ; et al.: New test of modulated electron capture decay of hydrogen-like  $^{142}\text{Pm}$  ions: Precision measurement of purely exponential decay. *Physics letters / B* B 797, 134800 (2019) DOI:10.1016/j.physletb.2019.134800

## 2.2 Department Materials Research

Head: Prof. Dr. Christina Trautmann, Technische Universität Darmstadt & GSI  
 Author: Prof. Dr. Christina Trautmann

The Materials Research Department operates the MAT platforms at the UNILAC and the SIS18 for a large number of users from many different fields of physics, biophysics and engineering. This includes the (i) M-branch for on-line and in situ monitoring of beam induced effects in materials by various spectroscopic techniques, (ii) beamline X0 for high through-put irradiations of up to 100  $\mu\text{m}$  thick samples including sample exposure from high fluences down to single ions, (iii) heavy-ion microprobe for targeted irradiations (precision below 1  $\mu\text{m}$ ) of electronic devices for space applications and biological cells, and (iv) Cave A at SIS18 for irradiations of mm thick samples. In addition, we have installed a new ultra-high vacuum setup at the extraction beamline of the CRYRING. The commissioning of the new setup is foreseen in the shutdown phase of 2020. At this beamline, highly charged or fully stripped heavy ions of energies of a few keV up to 10 MeV/u will be available for sample irradiation in combination with in-situ analysis. The high charge state of the ions is of interest for material and nanosciences, as the ions have beside their kinetic energy and an enormous potential energy resulting from the sum of the ionization energies of all missing electrons. New opportunities for material science at the upcoming FAIR facility are included in a recent review describing topics such as radiation hardness tests, high-pressure irradiations, radiation tests for electronic devices for space application etc. [1]. Short summaries of selected projects investigated during 2019 are presented below.

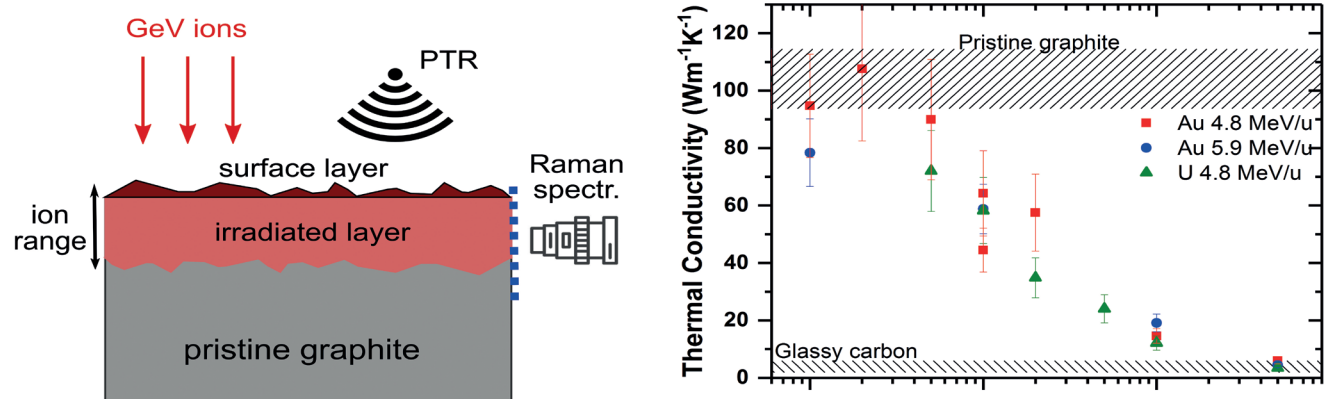


Figure 11. (Left) Scheme of sample irradiation and analysis by means of photothermal radiometry (PTR) from top layers and by Raman spectroscopy from sample cross sections. (Right) Degradation of thermal conductivity of fine-grained isotropic graphite as a function of fluence. [A. Prosvetov et al, Acta Materialia 184, 187 (2020), DOI:10.1016/j.actamat.2019.11.037].

### Highlights in 2019

#### Radiation hardness of FAIR materials

Carbon-based materials are considered to have favorable thermomechanical properties and excellent radiation hardness for the application as beam intercepting components. To estimate reliable operation performance and life time in extreme radiation environments, ion beam induced changes of thermophysical properties were characterized using frequency domain photothermal radiometry (PTR) complemented by Raman spectroscopy to monitor the underlying structural transformations. For high fluence irradiations corresponding to complete track coverage of the sample (Au or U ions of  $\sim 5 \times 10^{13} \text{ cm}^{-2}$ ), the thermal conductivity shows a drastic decrease from 95

to approximately  $4 \text{ Wm}^{-1}\text{K}^{-1}$ . Such a tremendous degradation can lead to inefficient heat dissipation and finally to thermomechanical failure of graphite beam dumps and production targets. For the new generations of high power accelerators, the risk due to largely reduced thermal conductivity values in high-dose environments has to be considered when designing and estimating the long-term operation conditions of beam-intercepting devices.

### Acoustic detection of heavy ions (Ionoacoustics)

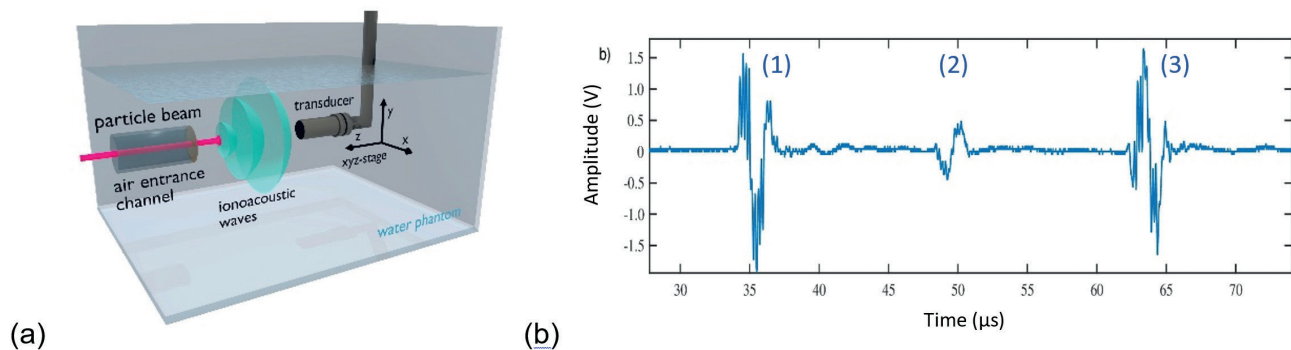


Figure 12. (a) Standard setup for ionoacoustic experiments: The ions enter a water filled acrylic basin through an air filled channel and a thin Kapton entrance window, are slowed down and finally stopped close to the Bragg peak. The induced ultrasound waves propagate towards a piezo-composite transducer (PZT) mounted on a remote controlled xyz-stage. (b) Ionoacoustic signals of 300-MeV/u  $^{124}\text{Xe}$  with 106 ions per pulse (micro-pulse length 100 ns) with (1) direct signal from ion pulse at Bragg maximum, (2) signal from entrance window, and (3) pulse signal reflected at window [S. Lehrack et al, Nucl. Instr. Meth. A 950, 162935 (2020), DOI: 10.1016/j.nima.2019.162935].

Travelling through dense media, energetic ion pulses produce transient acoustic waves mainly originating from the zone of maximum energy loss (Bragg peak) close to the end of the ion range. In recent experiments the acoustic signal was measured for short, intense bunches of C, Xe, and U ions (energies between 200 and 300 MeV/u) stopping in water. The acoustic signals were recorded with a piezoelectric lead zirconate titanate (PZT) transducer mounted on the axis of the incident ion beam (Figure 12). The range of the beam can be determined with sub-mm precision by calculating the time delay between zero-crossing of the direct signal of the ultrasonic pressure wave and the signal reflected at the entrance window. Ultrasonic pressure wave multiplied by the sound speed. Given the high energy resolution ( $<1\%$ ) and simplicity of the setting, this detection technique has a great potential for stopping power and range measurements as well as for monitoring short bunches of swift heavy ions within a large dynamic range from single ions up to highest intensities. In close collaboration with the group of Prof. W. Assmann of LMU Munich, future activities will test different transducer types, set up a 3D configuration by placing additional transducers normal to the beam axis, and determine upper and lower detection limits of low and high beam intensities.

## Ion-track nanotechnology

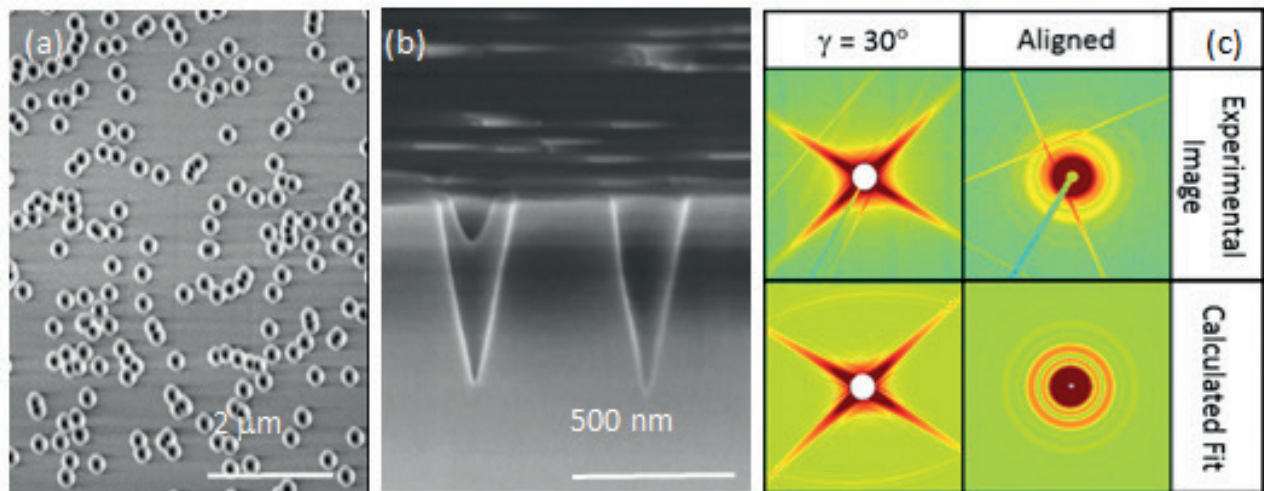


Figure 13. Scanning electron micrographs of conical etched pits in  $\text{SiO}_2$  irradiated with 185 MeV Au ions and etched with 5% HF: (a) plan view and (b) cross-sectional view; (c) measured and simulated SAXS pattern from conical etched pits in  $\text{SiO}_2$  irradiated with 1.1 GeV Au ions for the x-ray beam being aligned and tilted ( $\gamma = 30^\circ$  with respect to the track axis).

Many nanoscience projects are based on the fabrication of nanochannels by chemical etching of ion tracks predominantly in polymers. The technique provides remarkable control of the size, geometry and number density of nanochannels as well as the possibility to modify the surface by physical or chemical methods. The small channel diameter and large surface area enhance interactions between a solute and the walls, which in turn has an impact on nanofluidic transport phenomena. The group of our collaboration partner O. Azzaroni (La Plat, Argentina) provides exciting examples of how chemically functionalized track-etched nanostructures benefit analytical chemistry, and lead to new applications and functionalities [2]. By tuning the charge properties of the nanopore, the ion selectivity is controlled and ionic current rectification can be regulated by different stimuli. A field-effect transistor-like nanofluidic device based on the integration of a redox polymer onto the surface of nanochannels was developed. By sputtering gold on the tip side of a single nanopore and modifying the surface with poly-vinyl ferrocene, a reversible modulation of the iontronic behavior by the applied potential was obtained.

To provide better compatibility with existing Si technologies, the etching process for ion tracks in amorphous  $\text{SiO}_2$  was investigated by characterizing the influence of ion energy and etching conditions by small angle x-ray scattering (SAXS) by the group of P. Kluth (Canberra, Australia) [3].

## Selected publications of 2019

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## 2.3 Department Plasma Physics

Head: Dr. Vincent Bagnoud, GSI

Authors: Olga Rosmej, Johannes Hornung, Thomas Kühl, Sero Zähler, Stefan Götte, Victor Schanz, Paul Neumayer, Vincent Bagnoud

The plasma physics department is responsible at GSI for operating several experimental caves: the Z6 cave in the experimental hall of the UNILAC, the high-energy cave HHT close to the extraction beam line of the SIS18 and the petawatt target area at the laser facility 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 experiments aiming to study high energy density physics with intense ion beams and lasers at FAIR, both technically and scientifically.

The ramping up of the FAIR Phase-0 research program, where FAIR equipment and experimental concepts are being tested at GSI, has been a driving activity of the department in 2019. At the beginning of the year, the project to install a laser beamline between PHELIX and HHT was validated and officially started. This new infrastructure aims at demonstrating x-ray backlighting of matter, which has been heated by high energetic heavy ions, for the first time. This is one of the main ideas proposed for the plasma physics program at FAIR. Upon completion, laser pulses with energies up to 200 J at the second harmonic (wavelength 527 nm) and with nanosecond duration will become available at this experimental station. Although limited to mid-range x-rays, these will allow driving intense x-ray sources based on laser-produced plasmas, which will enable state-of-the-art x-ray probing techniques commonly used at high-energy density facilities worldwide. This demonstration will form the base for the planned diagnostics of dense plasmas produced with intense heavy-ion pulses at FAIR.

In addition, the high-energy short-pulse laser PHELIX was operated continuously in 2019. As in the past, 55% of the year was dedicated to experiments (18% setup, 37% beam time), serving 11 experiments. The topics under investigation by the international user groups were ranging from particle acceleration (electrons, ions) to the optimization of laser-driven secondary sources (neutrons, x-ray, gammas) and the study of laser-driven warm dense matter. 40% of the time was spent for maintenance: PHELIX is in operation for 12 years, therefore, substantial effort is needed to keep the system operational by continuous maintenance and upgrades. Most experiments were approved by the PHELIX and Plasma Physics Program Advisory Committee (PPAC), however two short internal beam times were performed and the rest of the time was shutdown (5%). As a noticeable improvement of the facility, a more reliable detection of the temporal contrast of the PHELIX pulse has been implemented [1] and the transfer of this technology to the industry has been initiated.

### Highlights in 2019

In experiments on laser-plasma interactions at moderate laser intensities around  $10^{19}$  W/cm<sup>2</sup> and near-critical-density (NCD) plasmas, the properties of ultra-relativistic electrons produced during the interaction was studied at PHELIX [2]. The ultra-relativistic electrons are generated in a sub-mm-long NCD plasma by the mechanism of direct laser acceleration in the plasma channel created by the propagating relativistic laser pulse. Low-density polymer foam layers of 300-450  $\mu$ m thickness pre-ionized by a well-defined nanosecond laser pulse were used as NCD targets. The electron spectra showed up to 10-fold increase of the electron apparent kinetic "temperature" from  $T_{\text{hot}} = 1.4 - 2$  MeV, measured for the case of the interaction of  $1-2 \times 10^{19}$  W/cm<sup>2</sup> laser pulse with a common used planar metallic foil, up to 14 MeV, for the case when the relativistic laser pulse propagates through a foam layer which is pre-ionized by ns-laser pulse, respectively. In this case, the maximum electron energy increases up to 80-90 MeV instead of 15 MeV (foil-case). This increase in electron energy was accompanied by a strong increase in the number of relativistic electrons and well-defined directionality of the ultra-relativistic electron beam, which was measured

to be  $10^\circ$  degree at FWHM.

The interaction of relativistic electrons with high Z materials causes MeV gamma-radiation that can drive photon-disintegration reactions resulting into neutron production. Using a combination of low density foam layers with mm-thick high-Z converter targets at  $10^{19}$  W/cm<sup>2</sup> laser intensity, we detected a 100 times higher reaction yield of Ta and Au isotopes generated in  $(\gamma, n)$  up to  $(\gamma, 5n)$  reactions with threshold energies  $E_\gamma = 7.5 - 40$  MeV, compared to the laser shots directly on to the converter foil at  $10^{21}$  W/cm<sup>2</sup> laser intensity. The reported results demonstrate an extremely high capability of high current well-directed relativistic electron beams generated in interaction of relativistic laser pulses with long-scale NCD plasmas to be used in novel laser assisted applications exploiting already existing laser systems such as PHELIX.

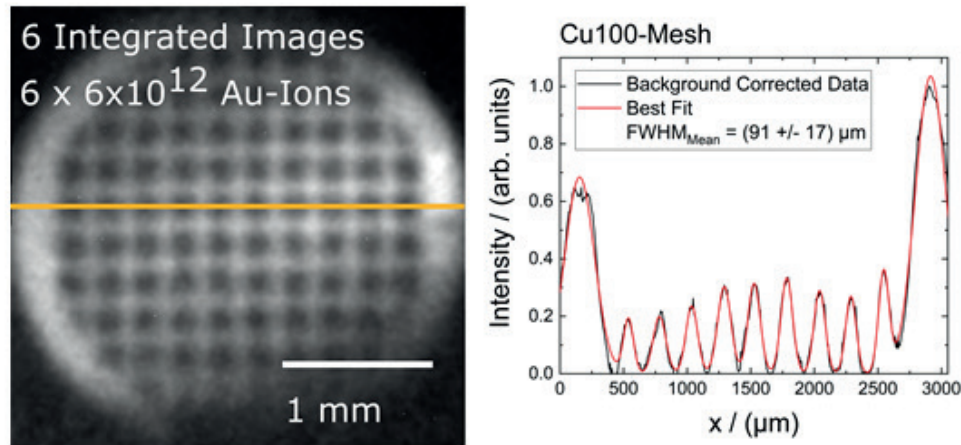


Figure 14. Mesh imaged with a pinhole camera onto the XCOT-system (left) and a corresponding lineout (right).

In experiments involving the ion beam, the x-ray emission generated by swift heavy ions crossing materials was studied under a new perspective, namely with the goal of using this radiation as a signature of the ion beam intensity distribution. A challenge of this method is the imaging of the x-ray source that we pursue using pinhole cameras and/or crystal spectrometers. Due to high radiation levels around the interaction area, transport of the signal far away from the target chamber and remote controlled detection are required. As a solution, the conversion of the x-ray signal into an optical one is an attractive solution. The x-ray Conversion to Optical Radiation and Transport (XCOT)-system was developed at the Goethe University, Frankfurt, in the frame of a BMBF-project aiming to develop a device, which meets the high demands in the application at the HHT cave during FAIR Phase-0 and later in the APPA Cave at FAIR. Pilot experiments were performed at the Z6 experimental cave to commission the XCOT-system. The XCOT-system consists of a 100  $\mu\text{m}$  thick CsI(Tl)-scintillator which converts the x-rays into visible light. That light is imaged by a lens system onto a micro channel plate based image intensifier unit in front of a sCMOS-camera. The UNILAC provided an 11.4 MeV/u Au<sup>26+</sup>-beam that irradiated foil- and mesh-targets of different materials and mesh widths. Multi pinholes were used to improve the signal-to-noise ratio. Cu-mesh's with mesh distances of 250  $\mu\text{m}$  (mesh width 60  $\mu\text{m}$ , see Figure 14) and smaller were used to determine the spatial resolution of the XCOT-system. By overlaying several of the images taken by the multi pinholes and then taking a lineout (see overlay of six Cu100-mesh images and diagram of the lineout marked in orange on the left of Figure 14), the heavy-ion beam distribution on target can be measured on shot.

Another emerging field is that of nuclear reactions induced by short-pulse, laser-accelerated proton bunches, that presents a new experimental approach to nuclear reaction physics. The on-going developments in laser acceleration of protons and light ions, and the creation of strong bursts of multi-MeV photons now provide a basis for novel nuclear physics experiments, because the instantaneous flux of laser-accelerated particles exceeds the capabilities of standard particle accelerators. In order to approach this new field, a method was realized to detect  $\gamma$ -ray and  $\beta$ -particle emission from the fission fragments in the presence of electromagnetic pulse (EMP) induced background from the laser-matter interaction allows sensitive nuclear spectroscopy on isotopes

and isomers with lifetimes down to around one second. Prior to the main experiment, an optimization of the proton source to achieve the highest possible particle flux took place. This was done by increasing the coupling efficiency between laser and target by changing the polarization of the laser with respect to the target. Using this optimization, PHELIX delivered an exponential proton spectrum with a cut-off energy of 70 MeV, containing  $10^{12}$  particles above 15 MeV, within a sub-nanosecond time window. Natural uranium foil targets contained in a gas-cell caught the ions, which trigger fission reactions on a short time scale. A fast gas flow transported the fission products over 12 m towards a carbon filter, where a high-purity germanium detector recorded the  $\gamma$ -ray emission. The  $\gamma$ -rays were compared to those of evaluated nuclear data tables, and the volatile fission fragment isotopes  $^{134}\text{I}$ ,  $^{136m}\text{I}$ ,  $^{137}\text{Xe}$ ,  $^{138}\text{Xe}$  and  $^{139}\text{Xe}$  have been identified. The detected isotopes in this first experiment include those that have lifetimes down to  $< 40$  s.

Another important aspect for the future FAIR experiments is the performance of laser-driven x-ray sources planned for volumetric diagnostics of ion-heated matter. Since this technique will be new, and to demonstrate their suitability for the foreseen diagnostic applications with the laser parameters planned at FAIR, we have performed an experiment at the Z6 experimental area. Laser pulses from both the nhelix and the PHELIX laser systems were used, with pulse energies up to 40 J (in 8 ns) and 160 J (in 1 ns), respectively. Focused down to spot sizes of about 50  $\mu\text{m}$ , these yield intensities from  $10^{14}$  to  $6 \times 10^{15}$  W/cm<sup>2</sup>. A variety of mid- to high-Z targets were irradiated, producing hot (few keV) highly-charged plasmas. Two crystal spectrometers recorded the x-ray emission spectra, while a pinhole camera determined the x-ray source size.

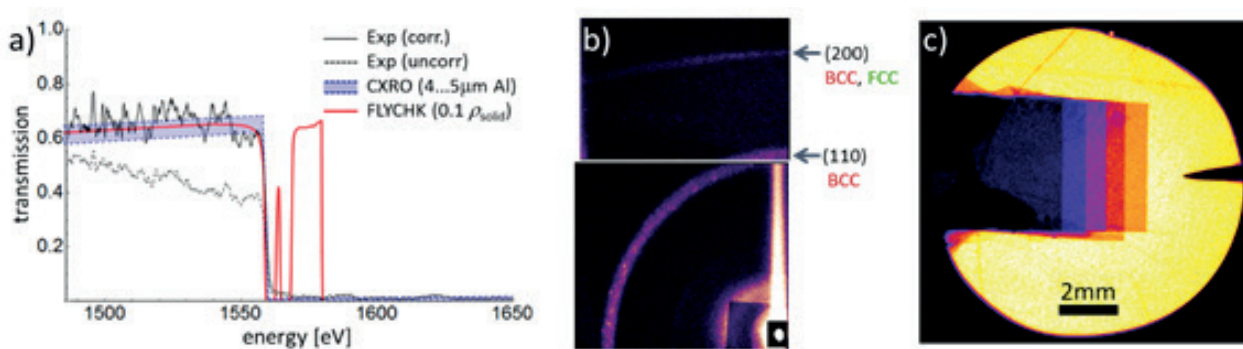


Figure 15. Left: XANES spectrum, middle: x-ray diffraction rings in iron, right: calibration plates for x-ray absorption.

During this experiment, a dual-channel focusing spectrometer based on two conically curved KAP-crystals (developed in collaboration with the FSU Jena) measured the x-ray emission in the spectral range around 1.6 keV. In this range, targets made from rare earth elements (Sm, Dy, Sm) exhibit strong M-band emission. The high density of emission lines results in a near continuous emission spectrum, suitable for x-ray absorption spectroscopy. As example, Figure 15 a) shows a single-shot high-resolution absorption spectrum through a 5  $\mu\text{m}$  thick aluminium foil in the vicinity of the Al K-edge. This so-called XANES (x-ray Absorption Near-Edge Spectroscopy) technique, has a high diagnostic potential, in particular to infer electron temperatures in samples at warm-dense matter conditions, detects edge shifts and shell rebinding, and provides access to the local ionic structure too.

The second spectrometer employing a highly-oriented pyrolytic graphite crystal covered the spectral range 4...9 keV, measuring the strong line emission from Helium-like ions from mid-Z metal targets (Ti, Fe, Ni, Cu). The x-ray yield increases strongly with laser intensity, with a more than 1000-fold increase from the lowest (nhelix) to the highest (PHELIX) energy laser pulses, underlining the need for high-energy laser pulses to efficiently drive these x-ray sources. At the highest intensities, the conversion efficiency (laser to x-ray energy) reaches values of nearly  $10^{-3}$ , yielding up to  $10^{14}$  photons at 4.5 keV. A prominent diagnostic application of such intense narrow-band x-ray sources is x-ray diffraction. Figure 15 b) shows as example the Debye-Scherrer rings from a 5- $\mu\text{m}$ -thick iron foil. For targets heated by heavy ions diffraction will allow to measure changes of the lattice constant due to thermal expansion, observe solid-solid phase transitions and indicate melting. Furthermore, the diffracted intensity can be related to the lattice temperature via the Debye-Waller-factor.

A high Z pinhole of 25  $\mu\text{m}$  diameter was used for the pinhole camera filtering was chosen to image x-ray energies  $> 4$  keV. X-ray source sizes between 50 and 150  $\mu\text{m}$  were measured, with a tendency to larger sizes at higher laser energies. A small source allows for point-projection x-ray imaging (Figure 15 c). Radiographic imaging of heavy-ion-driven samples would allow to observe evaporation and isentropic expansion, interface movement as a heavy material pushes into a lighter tamper, fracture and spallation events etc.

Another x-ray-based imaging technique is phase-contrast x-ray imaging that can yield significantly enhanced sensitivity to density variations than x-ray absorption radiography. This is a crucial advantage when imaging weakly-absorbing low-Z materials, or steep density gradients in matter under extreme conditions. At PHELIX, hard x-ray sources with few-micrometer source size are routinely realized by irradiating thin metal wires at relativistic intensity (above  $10^{18}$  W/cm<sup>2</sup>). The spatial coherence of such small x-ray sources has successfully been employed to produce high-resolution x-ray images with propagation-based phase-contrast, and the ultra-short duration allows to take snap-shots of laser-driven shock waves[3]. Detailed analysis of the data has shown that this method obtaining higher object definition and can reveal structural features that are undetectable using x-ray absorption techniques. Furthermore, it allows for quantitative analysis of the acquired image, producing highly-resolved density maps which can be directly compared to advanced radiation-hydrodynamic simulations.

## Outlook for 2020

The activities of the department will continue in 2020, building on the momentum acquired in 2019. One of the highlight activities will be the delivery and test of the electromagnets for the PRIOR II proton microscope at the high-energy cave HHT. Together with a group of JWGU Frankfurt we continue to develop a pulsed-power driver capable of performing under water wire explosions.

In parallel, the construction of the HIHEX platform at the HHT cave will go on with the delivery of the main components. In this project, a major milestone will be the delivery of the FAIR target chamber, which has been developed in a collaboration of the JWGU Frankfurt, TU Darmstadt and FSU Jena supported by the BMBF Verbundforschung.

These new developments should not have any impact on the PHELIX beamtimes in 2020, which will be planned in line with the previous years. The experiments planned for 2020 have been evaluated by the PHELIX and Plasma physics Advisory Committee (PPAC) in fall 2019 and will start in April 2020. In 2020, new calls for experiments at the plasma physics caves (Z6, PHELIX and HHT) will be issued for experiments in 2021 and 2022.

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## 2.4 Biophysics department

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



Figure 16. The International Biophysics Collaboration Meeting, held at the GSI Campus on May 20-22, 2019. The meeting was attended by 250 scientists from 25 countries in 5 continents Photos by G. Otto/GSI.

### Biophysics Collaboration at FAIR

The Biophysics Department studies the biological effects of high-energy heavy ions, and its applications to cancer therapy and radiation protection in space. The department is part of the APPA pillar at FAIR, and held its collaboration meeting at the GSI Campus on May 20-22, 2019 (Figure 16). FAIR will offer unique opportunities for biomedical research. The production of very high energy ( $\sim 10$  GeV/u) heavy ions is very important for studies in space radiation protection, both in biology and microelectronics. The high energy can also be used for particle radiography and theranostics, whereas the high intensity of the FAIR beams will allow using high-energy radioactive ion beams and ultra-high dose rates in particle therapy, and for the production of new radioisotopes [1]. The Biophysics collaboration has been structured with a spokesperson (Prof. Vincenzo Patera, University of Rome "La Sapienza", Italy), a deputy spokesperson (Dr. Yolanda Prezado, Institute Curie, Paris, France) and an executive committee including representative of all the major accelerator facilities in operation or under construction with programs in biomedical research (NICA, RAON, ELI, KVI, LNL, LNS, GANIL etc.). The Biophysics Collaboration is also editing a special issue of the journal "Frontiers in Physics" totally dedicated to biomedical research at new particle accelerators.

## Partnership with ESA



Figure 17. Group photo of students and faculty of the 1st ESA-FAIR Summer School in Darmstadt, September 15- October 1, 2019. Photos by G. Otto/GSI.

In the framework of the ESA-FAIR MoU signed in 2018, our department has further intensified the collaboration with the European Space Agency (ESA). Since 2010, we host the European ground-based program on space radiation protection called IBER (Investigation on Biological Effects of space Radiation). In April 2019, nine experimental groups from Germany, Italy, Belgium and Romania performed their experiments in the framework of the FAIR Phase-0 using a beam of 1 GeV/u  $^{56}\text{Fe}$ . The researchers will repeat the experiments during the FAIR Phase-0 beamtime in 2020. In December 2019 ESA has selected the experiments for the experiments for the future IBER program, that will be performed in 2021-22.

Within the MoU, ESA and FAIR also agreed to organize a Summer School in Space Radiation Protection (Figure 17). The 1<sup>st</sup> school was held in September 2019 in Darmstadt. Fifteen graduate students from Germany, Italy, Portugal, Greece, Czech Republic, Belgium, Russia, and USA spent one week at ESOC for lectures and site visits, and one week at GSI for experiments. Students had different background (Physic, Biology, Engineer, Geology), nevertheless, they worked perfectly together. An outstanding international faculty was assembled, including the astronaut Dr. Thomas Reiter and the founder of the Biophysics department Prof. Gerhard Kraft.

## FAIR Phase-0

In the framework of the FAIR Phase-0 beamtime in 2019, our group conducted several experiments selected by the BIO-PAC or by ESA (IBER program; see above). The 13 BIO-PAC experiments focused on applications of high energetic  $^{12}\text{C}$  beams, including radiobiology and medical physics experiments. Part of the beamtime was also used for commissioning of FAIR devices, specifically a new scanner control and target handling system (Figure 18). Some of the results of these experiments will be published in 2020.

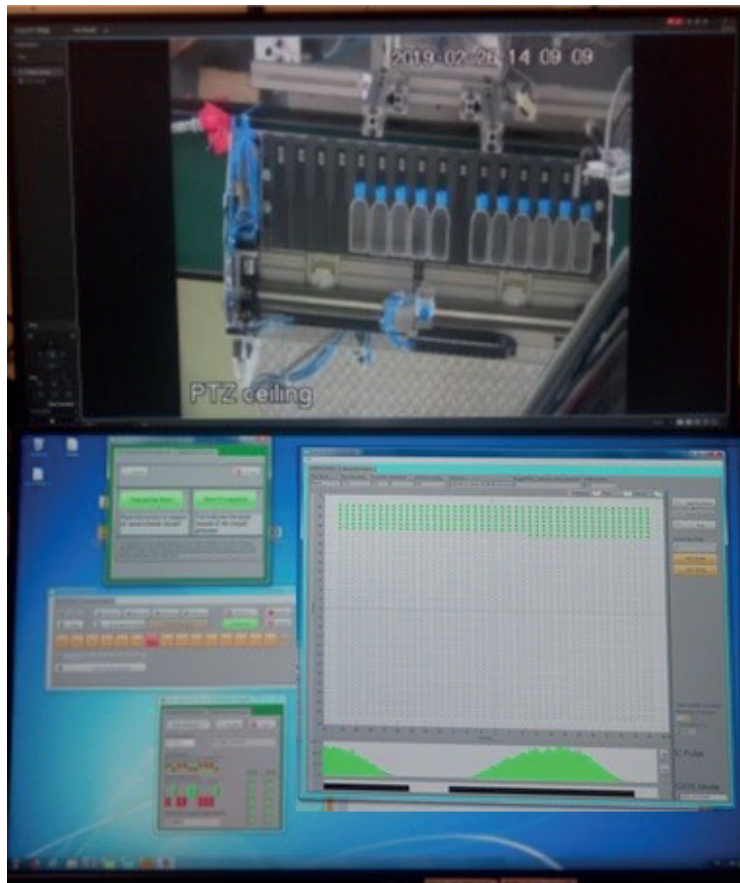


Figure 18. Commissioning of the new scanner control and target handling system for FAIR. Commissioning was successfully completed in Cave A using C-ions in the 2019 FAIR Phase-0 beamtime. Screen shot taken by M. Scholz during the irradiation.

## Highlights in 2019

### Particle therapy for heart arrhythmia: biological mechanism

Heavy ions can be used as an alternative to catheter ablation for the treatment of heart arrhythmia, a relatively common cardiac disease that leads to increased risk of stroke. We tested this hypothesis in a swine model in 2015 demonstrating that a single high dose of high-energy  $^{12}\text{C}$ -ions can induce interruption of the cardiac impulse propagation and ablation in the target area that resembles the effect of the microwaves emitted by the catheter.

Since our pilot experiments, the interest in this technique is growing. Several patients have been treated for ventricular tachycardia using X-ray stereotactic radiotherapy in USA, and in December 2019 a first patient has been treated with high-energy protons at CNAO (Pavia, Italy). In 2019 we published the full histological and molecular analysis of the pigs' heart samples irradiated with C-ions at GSI during the pilot project [2] in collaboration with Mayo Clinics (Rochester, USA) and the University of Heidelberg. Immuno histological analysis of the target tissue showed long-lasting vascular damage, fibrosis and loss of polarity of targeted cardiomyocytes. We conclude that the observed physiological changes in heart function are produced by radiation-induced fibrosis and cardiomyocyte functional inactivation. No effects were observed in the normal tissue traversed by the particle beam, suggesting that charged particles have the potential to produce ablation of specific heart targets with minimal side effects.

## Hibernation and radioprotection

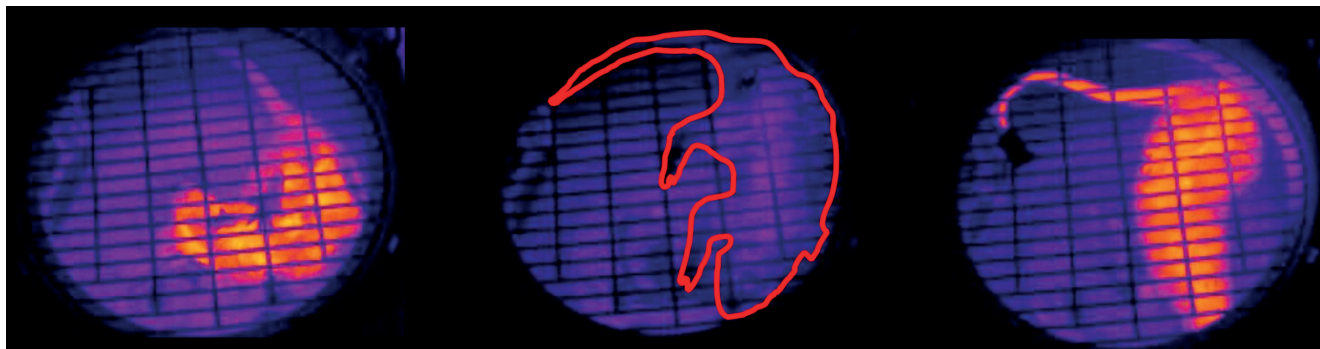


Figure 19. Induction of synthetic torpor in a rat as visualized by an infrared thermal camera. After 2 hrs from GABA inhibition, the rat is cold (contour is designed). Torpor can be reverted by stopping GABA inhibition in the raphe pallidus (right picture). Image courtesy of the University of Bologna, license ccby4.

Hibernation had been proposed as a tool for human space travel. However, the hypothesis was confined to science fiction for years because humans (unlike other mammals such as squirrels or bears) do not go into hibernation. In recent years, a procedure to induce a metabolic state known as “synthetic torpor” in non-hibernating mammals was successfully developed. Synthetic torpor may not only be an efficient method to spare resources and reduce psychological problems in long-term exploratory-class missions, but may also represent a countermeasure against cosmic rays. In fact, previous experiments with squirrels showed increased radioresistance when the animals were irradiated in hibernation. We have now shown for the first time that rats irradiated in synthetic torpor are more radioresistant compared to animals exposed in normothermic conditions (Figure 19) [3].

In the experiments, in collaboration with the University of Bologna and INFN (Italy), rats were irradiated with a single sub-lethal dose of 3 Gy. Histological analysis of liver and testicle showed a reduced toxicity in animals irradiated in torpor compared to controls irradiated at normal temperature and metabolic activity. Several genes involved in the DNA damage signaling were downregulated during synthetic torpor. These data suggest that synthetic torpor can be an effective strategy to protect humans during long term space exploration of the solar system.

## Outlook for 2020

We will take part in the FAIR Phase-0 block in early 2020, both with BIO-PAC experiments with C-ions and ESA-IBER experiments with Fe-ions. The executive committee of the Biophysics Collaboration will meet in Rome in February 2020. The new BIO-PAC will select the experiments for the future FAIR Phase-0 in June 2020. The 2<sup>nd</sup> ESA-FAIR Summer school will be held on September 13-29, 2020.

## Selected publications of 2019

- [1] Durante, M. ; Golubev, A. ; Park, W.-Y. ; et al.: Applied nuclear physics at the new high-energy particle accelerator facilities. *Physics reports* 800, 1 - 37 (2019) DOI:10.1016/j.physrep.2019.01.004
- [2] Rapp, F. ; Simoniello, P. ; Wiedemann, J. ; et al.: Biological Cardiac Tissue Effects of High-Energy Heavy Ions – Investigation for Myocardial Ablation. *Scientific reports* 9(1), 5000 (2019) DOI:10.1038/s41598-019-41314-x
- [3] Tinganelli, W. ; Hitrec, T. ; Romani, F. ; et al.: Hibernation and Radioprotection: Gene Expression in the Liver and Testicle of Rats Irradiated under Synthetic Torpor. *International journal of molecular sciences* 20(2), 352- (2019) DOI:10.3390/ijms20020352



### 3. Research of the Compressed Baryonic Matter departments

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

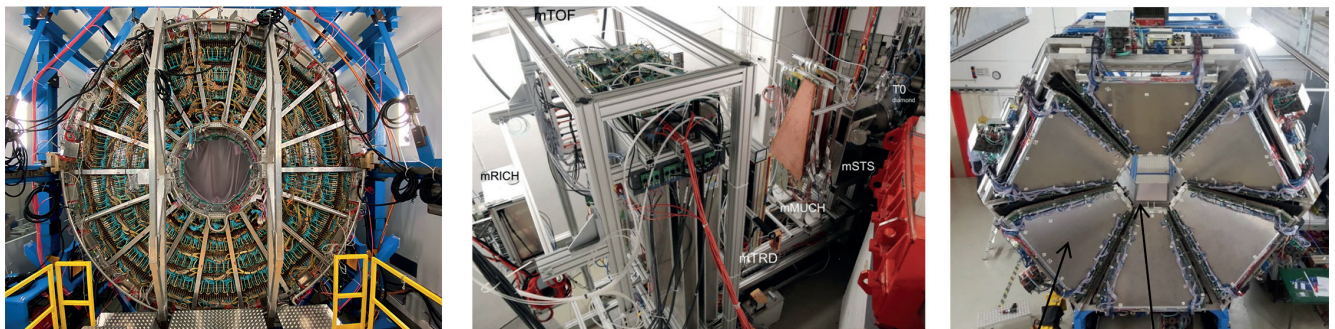


Figure 20. (From left to right) Fully instrumented endcap of the ALICE TPC (photograph by C. Lipmann), mCBM detector arm (left side facing the target) and a front-view of the new HADES ECAL.

2019 has been a very busy year witnessing the first production beam time in the context of FAIR Phase-0, the start-up of the mini-CBM system commissioning and the installation of the new read-out chambers for the ALICE Time Projection Chamber (TPC). This was pursued in parallel to substantial analysis and simulation activities.

A total of 72 read-out chambers were exchanged to complete the upgrade of the ALICE TPC which is now prepared to operate at interaction rates of 50 kHz for Pb-Pb collisions during Run 3 and 4 (see Figure 20 left panel). The amplification of the electron cloud, created along the charged particle tracks in the active TPC volume, is now accomplished by four layers of gas electron multiplier (GEM) foils, a technology which guarantees minimal ion backflow without operation of a gating grid. CBM has started to install a single arm detector station in Cave C based on CBM pre-series detector modules (Figure 20 middle panel). The set-up will enable commissioning of the free-flow signal digitization and acquisition as well as the online reconstruction of  $\Lambda$  weak decay signatures. HADES has completed several detector upgrades in time and accomplished a beam time measuring Ag+Ag collisions at 1.568 AGeV. In addition, HADES started to install the new forward detection system aiming at an enhanced performance of exclusive channels reconstruction in pion-, proton- and deuteron-induced reactions. Figure 20 (right panel) shows a front view of the new HADES ECAL.

With its contributions to the three experiments ALICE, CBM and HADES, the research pillar conducts research on extreme states of QCD matter over a wide range of densities and temperatures. The key objective is to advance our understanding of the strong force and properties of extended strongly interacting systems. This involves the investigation of the phase structure of strongly interacting matter and the search for landmarks of the QCD phase diagram like phase transitions, the understanding of color confinement, and a detailed characterization of the dynamic properties of matter under extreme conditions of high temperature and/or density. While beam energies at the LHC exceed by factor of 1000 the one at the GSI SIS18, many of the observables addressed are similar and require the same analysis strategies. The research division is in the process to prepare respective software packages such that they can be easily adopted to the various experiments. Examples are the reconstruction of flow phenomena, the extraction of the electromagnetic continuum radiation and the reconstruction of particle decay chains via a powerful vertexing package. Together with the theory division, a software platform is developed which will allow the comparison of model calculations with data in an easy-to-use and transparent way.

Intense cooperation exists also with the research infrastructure departments DTL (prototyping and construction of the CBM Silicon Tracking Station, construction and test of the larger GEM read-out chambers for the ALICE TPC), EEL (readout of the HADES ECAL, RICH and Forward detector) and the IT department. The CBM department is also involved in activities aiming at the instrumentation and preparation of the Russian Mega Science project NICA, with its experiments BM@N and MPD. The division has a broad expertise in heavy-ion experiments and provides ideal conditions to educate the next generation of scientists who will shape the FAIR physics in a decade from now.

## 3.1 Department ALICE at GSI

Head: Prof. Dr. Silvia Masciocchi, Universität Heidelberg & GSI

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

Fundamental properties of strongly interacting matter can be studied in a unique way in high-energy nucleus-nucleus collisions. While the regime of high net-baryon density is investigated currently with the HADES experiment at GSI and, in the future, with the CBM experiment at FAIR, the regime of high temperature and vanishing net-baryon density is accessible at the Large Hadron Collider (LHC) at CERN, where ALICE is the flagship experiment for the characterization of the quark-gluon plasma (QGP), the state of de-confined and thermalized strongly interacting matter produced in heavy-ion collisions at unprecedented energies as provided by the LHC.

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 management and coordination of the experiment.

### Highlights in 2019

#### Physics output

After four weeks of collisions of lead nuclei at a center-of-mass energy of  $\sqrt{s_{NN}} = 5.02$  TeV the second experimental campaign of the LHC came to its end in December 2018. ALICE recorded more than the expected integrated luminosity of  $1 \text{ nb}^{-1}$ , and the analysis of this large data set is in full swing since then. The ALICE-GSI team is leading the analyses related to various observables crucial for the characterization 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 2019. In preparation for the "28<sup>th</sup> International Conference on Ultra-relativistic Nucleus-Nucleus Collisions", the most important conference in the field which took place in November 2019 in Wuhan (China), ALICE submitted 18 manuscripts for publication, five of them with dominant, if not exclusive, contributions from GSI. One focus of the ALICE-GSI group is the physics of heavy charm and beauty quarks, which are unique probes for the QGP. Measurements of the production of  $J/\psi$  mesons, i.e. bound states of charm and anti-charm quarks, are sensitive to de-confinement and can give insight into the phase structure of strongly interacting matter. Open heavy-flavour hadrons, carrying one heavy and one light quark, give access to the dynamics of the evolving QGP, and their production was investigated at GSI via measurements of electrons from semileptonic decays of heavy-flavour hadrons as well as the full reconstruction of their decays in hadronic channels. Another focus of the group is the investigation of collective flow in heavy-ion collisions, which is addressed via measurements of light but also heavy-flavor hadrons. Particular highlights in 2019 were the first measurements of the charge-dependent directed flow in Pb-Pb collisions at the LHC, which might be a unique way to study effects due to the strong electromagnetic fields prevailing in the initial phase of the collision. The third focus is related to the production of loosely bound light nuclei, hyper-nuclei, and the corresponding anti-nuclei. Their production mechanisms are not understood but of fundamental relevance, not only in the context of elucidating properties of the strong interaction. For dark-matter searches with space-bound experiments anti-nuclei yields measured at the LHC provide a crucial background estimate. The ALICE group is centrally involved in all of the studies.

## ALICE Upgrades

2019 was the first year of the LHC Long Shutdown 2 (LS2). During this pause of the accelerator operation, ALICE is undergoing major upgrades in order to become able to record data in continuous mode with the majority of its detector systems. This will enable ALICE to profit fully from the significantly higher heavy-ion collision rate of 50 kHz, which is expected at the LHC from the year 2021 onward. The ALICE-GSI group, together with the detector laboratory and the scientific computing teams, plays a central role in the upgrade of the Time Projection Chamber and in the development of the new Online-Offline facility and software framework (the O<sup>2</sup> project).

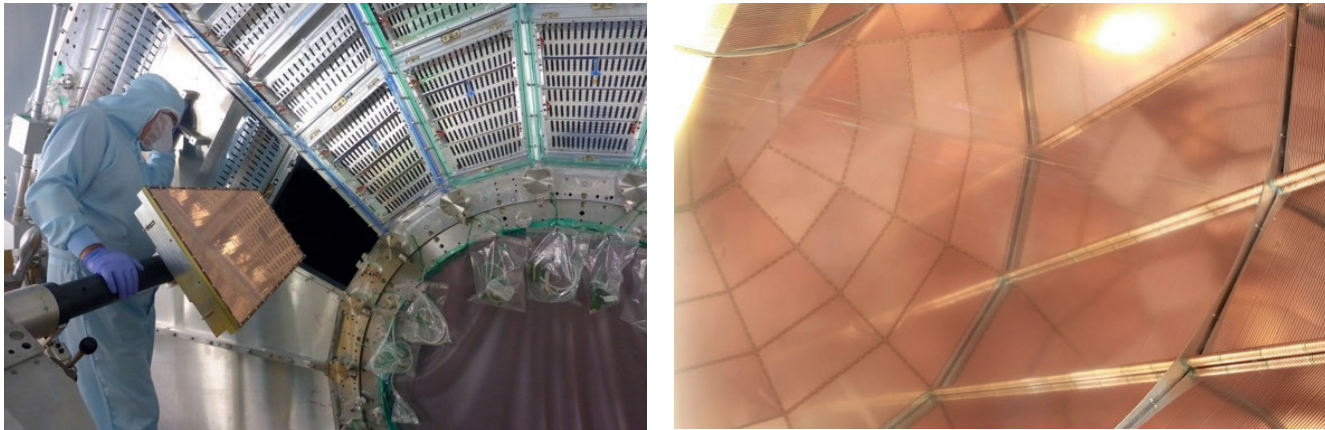


Figure 21. ALICE TPC upgrade: Insertion of a GEM readout chamber (left panel, photograph by P. Gasik); Reflection of GEMs on the central electrode of the TPC before the insertion of the last chamber (right panel, photograph by P. Gasik).

In order to achieve continuous sensitivity for the large ALICE TPC (where particle detection relies on the drift of a high density of charges in the 90 m<sup>3</sup> gaseous volume), it was mandatory to replace entirely the charge detection and readout systems. In the course of 2018, the construction of new TPC readout chambers equipped with Gas Electron Multiplier foils (GEMs) was completed: GSI provided 20 large area Outer ReadOut Chambers. In March 2019, the TPC was removed from the ALICE experimental hall (after 4435 days spent in the cavern) and installed in a clean room close to the LHC interaction point 2. The original multi-wire proportional chambers were removed and the 72 new GEM chambers were installed by September 2019 (see Figure 21). After the installation of the readout electronics (with more than 3000 front-end cards), of the high-voltage system and all other services, the TPC was brought back to full operation in a surface building at CERN in November. An intense pre-commissioning phase is ongoing, using cosmic rays, laser and pulser signals. In addition, a powerful x-ray source is used to irradiate the TPC and simulate the high current load on the readout chambers, as expected in the 50 kHz Pb-Pb campaign in 2021. This first commissioning phase is essential to guarantee the excellent and safe operation of the new GEM TPC for further 10 years in the ALICE experiment.

The new GEM TPC will return to the ALICE cavern in April 2020, and the full commissioning period will take place in the underground hall, in the final detector position. Several members of the GSI team are involved in the TPC instrumentation work, commissioning plans, as well as in the preparations of the software needed for the calibration and reconstruction of the upgraded detector.

This software will be part of the entirely new online-offline framework which is being developed in ALICE, called O<sup>2</sup>. A raw-data stream of more than 3 Tb/s, as produced by the upgraded detectors, requires a fully new readout and online processing scheme: synchronous and asynchronous detector calibration and track reconstruction will be performed in the new First Level Processors and Event Processing Nodes (EPN), in order to reduce the data volume to be written to disk, preserving the relevant information. GSI contributes both to the design and test of the EPN farm and to the development of the needed software in the so-called ALFA framework. This is an effort which maximally profits from the synergies between developments in ALICE and for the FAIR experiments.

## Outlook for 2020

2020 is the second and last year of the LHC LS2. Highest priority will be given to completing the installation and commissioning of the upgraded detectors in ALICE. All elements of the new O<sup>2</sup> project will need to be purchased and installed, to prepare for the global ALICE commissioning in early 2021 and the start of the LHC Run 3 in May 2021. Simultaneously, the physics analysis of Run 2 data will continue. Major new results have been submitted for publication in the refereed literature already.

## Selected publications of 2019

- Acharya, S. ; Torales - Acosta, F. ; Adamova, D. ; et al. (ALICE Collaboration):  $\Lambda_c^+$  production in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Physics letters / B B 793, 212 - 223 (2019) DOI:10.1016/j.physletb.2019.04.046
- Acharya, S. ; Adamova, D. ; Adhya, S. P. ; et al. (ALICE Collaboration): Inclusive  $J/\psi$  production at mid-rapidity in pp collisions at  $\sqrt{s} = 5.02$  TeV. Journal of high energy physics 2019(10), 84 (2019) DOI:10.1007/JHEP10(2019)084
- Acharya, S. ; Adamová, D. ; Adhya, S. P. ; et al. (ALICE Collaboration):  $^3\text{H}$  and anti- $^3\text{H}$  lifetime measurement in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV via two-body decay. Physics letters / B B 797, 134905 (2019) DOI:10.1016/j.physletb.2019.134905

## 3.2 Department CBM at FAIR

Head: Prof. Hans Rudolf Schmidt, Eberhard Karls Universität Tübingen & GSI

Author: Prof. Hans Rudolf Schmidt, Dr. Jörg Lehnert, Dr. Ch. Sturm

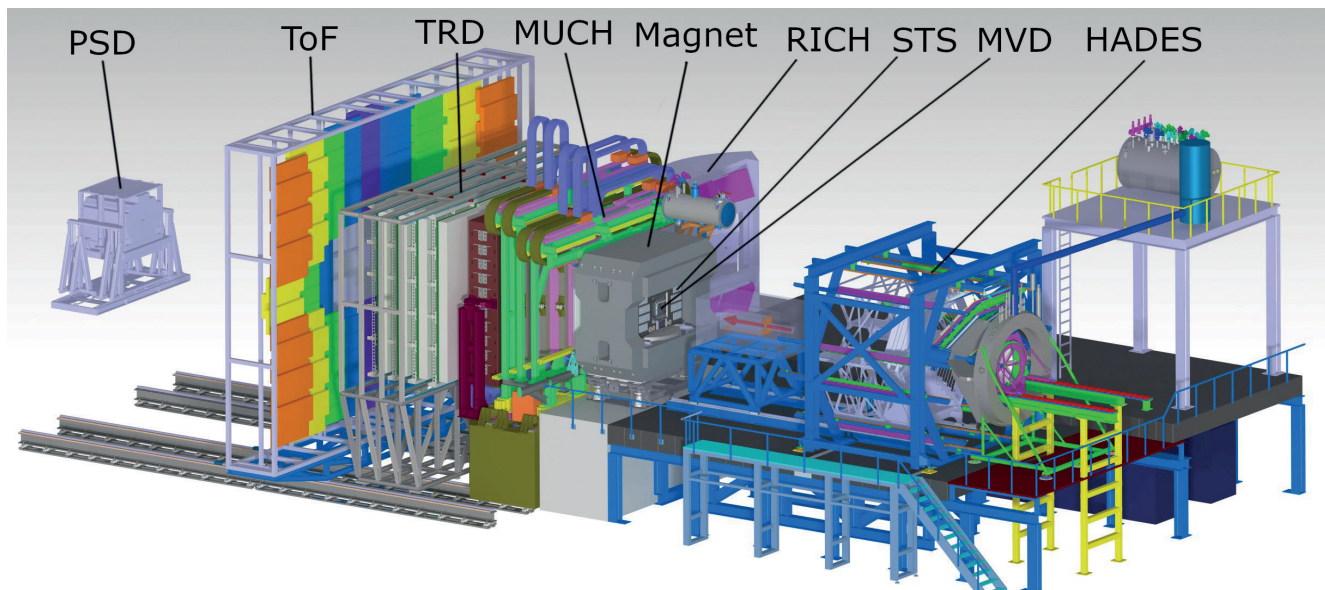


Figure 22. The CBM experimental setup. The CBM components are described in the text. For muon measurements, the RICH will be exchanged by the MuCh which is shown in a parking position to the right of the beam axis.

The Compressed Baryonic Matter experiment is one of the four scientific pillars of the FAIR accelerator facility. The major goal of CBM research is to investigate strongly interacting QCD matter at high net-baryon densities using high energetic nucleus-nucleus collisions. The CBM detectors are designed to study collective flow of hadrons, together with rarely produced probes like multi-strange particles, hyper nuclei, event-by-event correlations and fluctuations and thermal radiation. These measurements will be performed at reaction rates up to 10 MHz.

The planned CBM experimental setup is depicted Figure 22 and includes the following components:

- a superconducting dipole magnet;
- a Micro Vertex Detector (MVD) consisting of four layers of silicon Monolithic Active Pixel Sensors (MAPS) for precise vertex determination of open charm decays;
- a Silicon Tracking System (STS) based on double-sided silicon microstrip sensors arranged in eight stations inside the magnetic field for momentum determination of charged particles
- a Time-of-Flight (TOF) wall based on Multi-Gap Resistive Plate Chambers (MRPC) with low resistivity glass essential for high-rate operation,
- a Ring Imaging Cherenkov (RICH) detector comprising a CO<sub>2</sub> radiator, and a UV photon detector realized with multi-anode photomultipliers for electron identification,
- a Transition Radiation Detector (TRD) for pion suppression, particle tracking, and identification using specific energy loss,
- a Muon Chamber (MuCh) system for muon identification consisting of a set of gaseous micropattern chambers sandwiched between hadron absorber plates made of graphite and iron,
- a Projectile Spectator Detector (PSD) for event characterization, and
- a First-Level-Event-Selection (FLES) system for online event reconstruction and selection.

The CBM department at GSI together with colleagues from the detector laboratory and experiment electronics are involved in the design and construction of the CBM STS, the read-out electronics for the TOF detector, the analysis and simulation framework, and has taken over responsibilities in coordination and organization of the collaboration work.

### STS Frontend ASIC

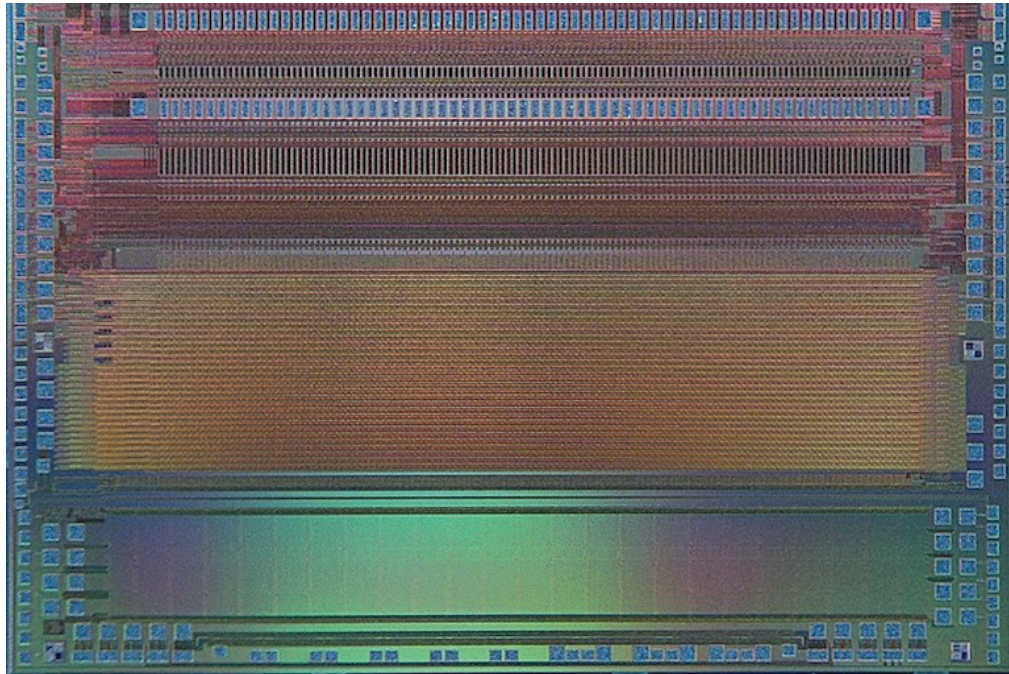


Figure 23. STS-XYTER v2.1 frontend ASIC

The version 2.1 of the STS-XYTER frontend ASIC shown in Figure 23 with multiple significant functional improvements became available in the beginning of 2019. It was extensively tested and characterized in various setups. A detailed test program was executed in lab setups in order to verify the full digital functionality and to characterize the performance of the analogue frontend part in terms of, e.g. signal gain, high rate capabilities and noise characteristics. Further tests included irradiation tests at various facilities to investigate the effects of total ionizing dose on the device operation and studies to verify the immunity to electrostatic discharge effects. STS modules with the STS-XYTER v2.1 were operated in heavy ion beam tests in the mCBM setup at SIS18 and with proton beam at COSY.

As a result of the comprehensive test program, the STS-XYTER version 2.2 was submitted with minor modifications after the ASIC Engineering Design Review in December 2019.

## Commissioning of mCBM@SIS18

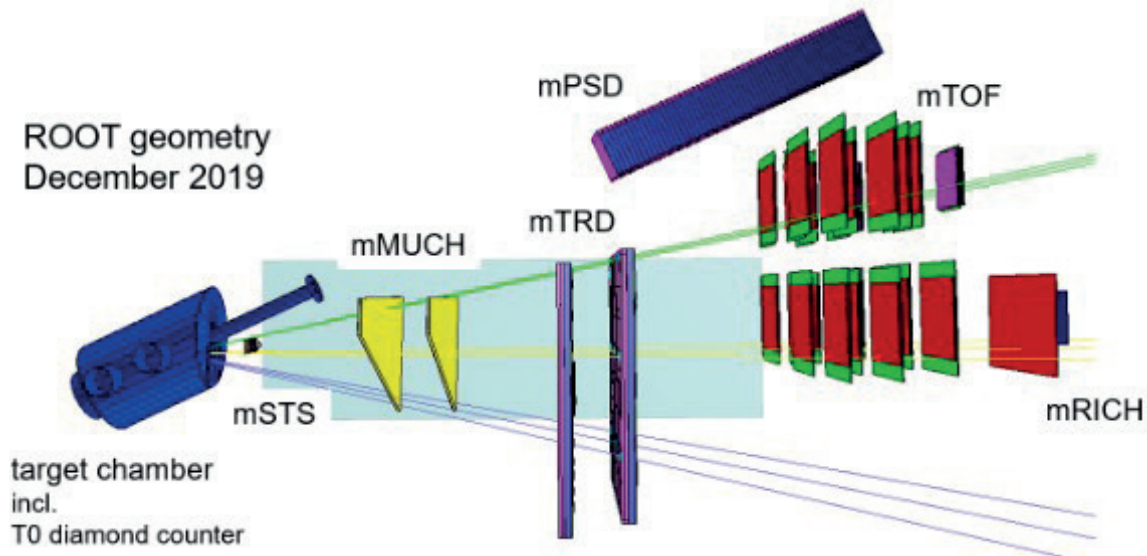


Figure 24. The picture shows the ROOT geometry of the mCBM setup as of December 2019, beam enters to the left.

To commission and optimize all components and their complex interplay including firmware and software under realistic conditions the CBM full-system test-setup mCBM@SIS18 (“mini-CBM” or short mCBM) comprising pre-series components and final prototypes of all CBM detector subsystems and their read-out chains has been constructed in 2017 and 2018 at the present SIS18 facility of GSI/FAIR. The installation site of mCBM is the detector test area named Cave-D (HTD) situated at the beam entrance of the experimental area Cave-C (HTC) hosting the nuclear structure experiment R<sup>3</sup>B.

As a part of the FAIR Phase-0 program, the commissioning of mCBM with beam has started during the machine engineering runs in December 2018, followed by the main commissioning beam time in March 2019, and again in November/December 2019 during the machine engineering runs. As depicted in the top panel of Figure 24, the mCBM test-setup is positioned downstream of a solid target under a polar angle of about 25° with respect to the primary beam.

While the completion of mCBM is ongoing, the setup included end of 2019 (see Figure 24):

- the time-zero (T0) diamond counter, consisting of eight vertical strips of 2 mm width, mounted inside the target chamber, 20cm upstream the target,
- the first station (station-0) of the mSTS subsystem equipped with one STS module,
- the mMUCH consisting of two GEM counters, with (almost) complete read-out electronics,
- the mTOF, fully equipped with five super-modules containing five RPC counters each, configured to a triple and double stack, enabling internal tracklet search as well as detailed efficiency studies,
- the mRICH, fully equipped with two aerogel radiators and 36 MAPMTs, which are read-out by 72 DiRICH modules developed at GSI in the electronics laboratory.
- the mPSD with one PSD module readout by a PANDA ADC board and
- the mTRD containing two TRD’s multi-wire proportional counters MWPCs.

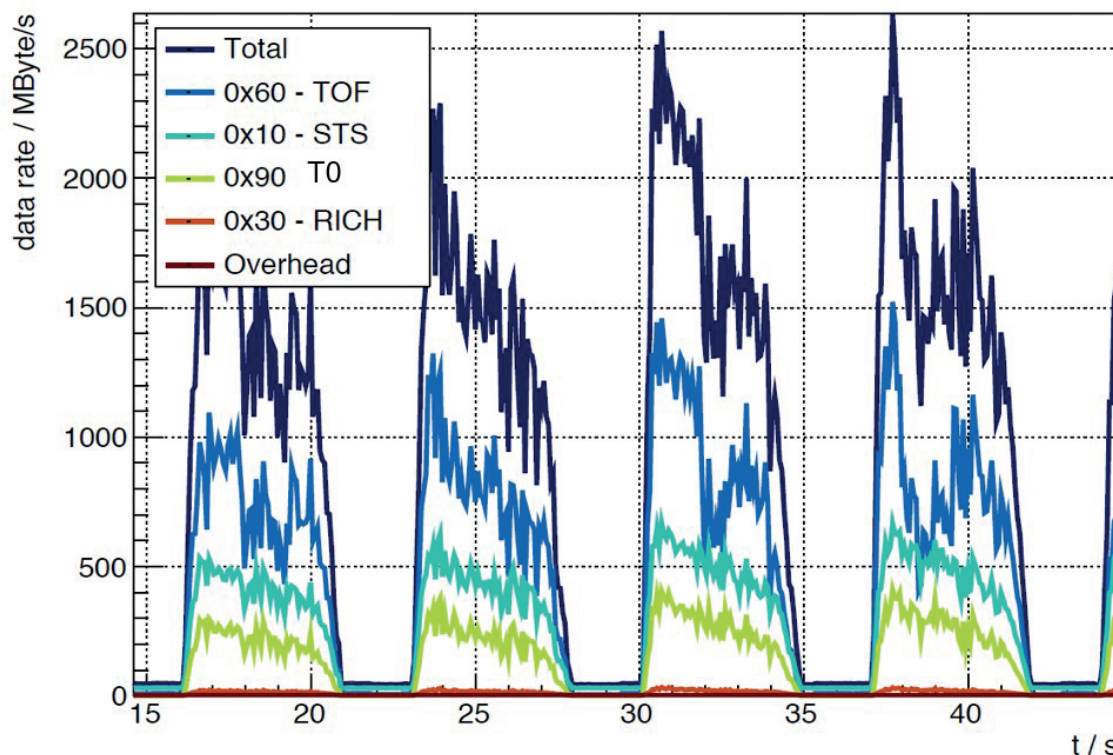


Figure 25. Data rates observed by the FLES processing nodes inside the GreenITCube during high-rate tests 2019. The total data rate and the data rates of the individual sub-systems are shown as function of time

First high-rate tests could be performed during the March 2019 run, using  $\text{Ag}^{45+}$  beam with an incident kinetic energy of 1.58 GeV/u. Running with beam intensities up to  $10^8$  Ag ions/s, resulting to a top collision rate of 10 MHz, data rates up to 2.5 GB/s (cf. Figure 25) have been observed by the processing nodes of the first-level-event-selector (FLES) inside the Green IT Cube during data taking.

To ensure proper beam alignment which is essential at high beam intensities, the beam diagnostics of the mCBM beam line has been upgraded by the beam diagnostic team of GSI in the second half of 2019. During the machine engineering runs in November and December 2019 the two new scintillation screens, located in front of the focusing units and inside the mCBM cave, both imaged by digital CCDs, have been successfully commissioned. Hence, beam alignment and focusing could be significantly improved.

First preliminary results obtained during data taking in December 2019 are depicted in Figure 26. The upper panels show spatial correlations between the mTOF and mMUCH subsystem (x left, y right), the lower figures between the mTOF and mRICH. Data on Ar + Au collisions at 1.7 A GeV were taken with a common, synchronized data transport of all subsystems. Individual time-offsets of the subsystems have been corrected during unpacking, fine-calibration procedures have not been applied. After cluster and hit finding, a simplified event building and event selection has been performed by cluster-finding within a fixed time window and a minimal requirement on the start time and mTOF multiplicity.

The observed time and spatial correlations between detector subsystems demonstrate a first conceptual proof of the free-streaming DAQ system of CBM. A detailed analysis is ongoing and further tests on the synchronization stability e.g. in dependence of the collision rate and data load need to be performed during the upcoming commissioning beam campaign in 2020. As the next steps, completion of the detector subsystems as well as major DAQ upgrades towards the final configuration to be used for the CBM experiment are foreseen.

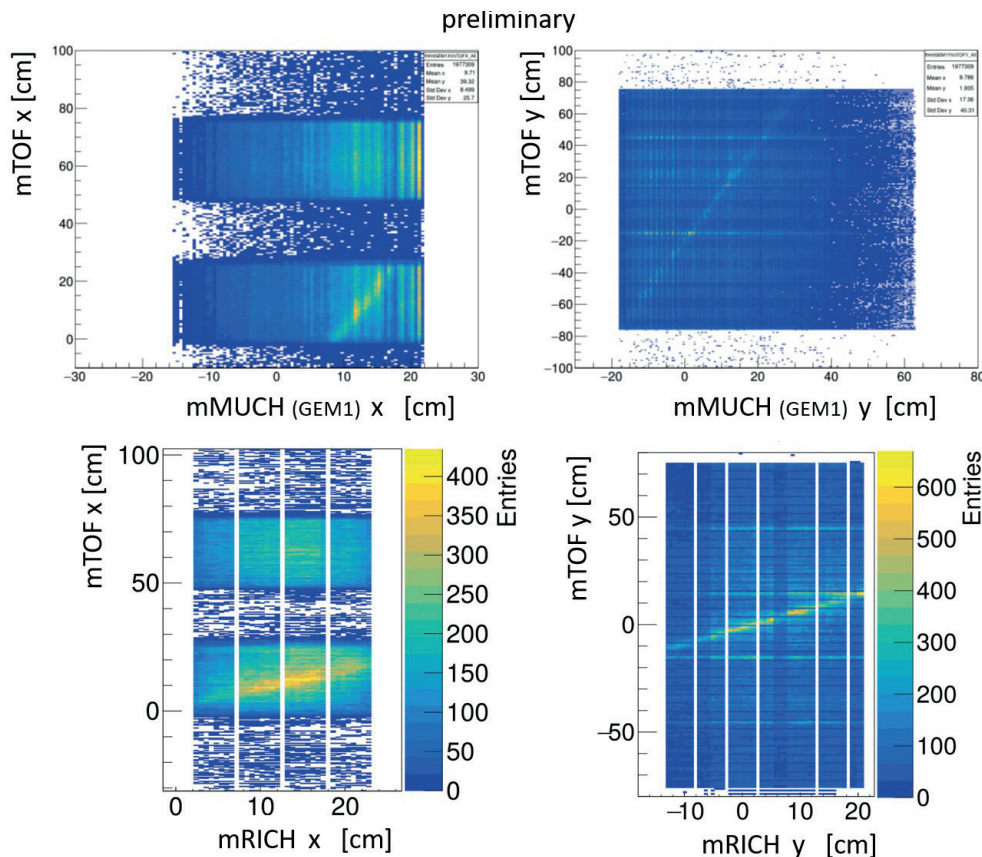


Figure 26. First preliminary results obtained during December 2019 – the upper pictures show spatial correlations between the mTOF and mMUCH subsystem (x left, y right), the lower figures between mTOF and mRICH.

## Outlook for 2020

2020 is a decisive year for the building of the CBM experiment: pre-series production of the key tracking detector of CBM, the STS, will be launched in fall 2020, following years of intense research and development of the detector system, as well as on assembly and quality assurance technologies. The STS teams at GSI, KIT, JINR and the university groups in Cracow and Tübingen will work closely together to meet the challenging goal to assemble, test and install almost thousand modules of the silicon tracker within the upcoming four years. Another key feature of CBM, the high-rate, triggerless data acquisition chain is under comprehensive studies with realistic conditions in the mCBM setup at an SIS18 beamline and will continue in 2020.

## Selected publications of 2019

- Lavrik, E. ; Frankenfeld, U. ; Mehta, S. ; et al.: High-precision contactless optical 3D-metrology of silicon sensors. Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A 935, 167 - 172 (2019) DOI:10.1016/j.nima.2019.04.039
- Senger, P.: Exploring Cosmic Matter in the Laboratory—The Compressed Baryonic Matter Experiment at FAIR. Particles 2(4), 499 - 510 (2019) DOI:10.3390/particles2040031
- Karpushkin, N. ; Finogeev, D. ; Golubeva, M. ; et al.: The Projectile Spectator Detector for measuring the geometry of heavy ion collisions at the CBM experiment at FAIR. Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A 936, 156 - 157 (2019) DOI:10.1016/j.nima.2018.10.054

### 3.3 Department HADES

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

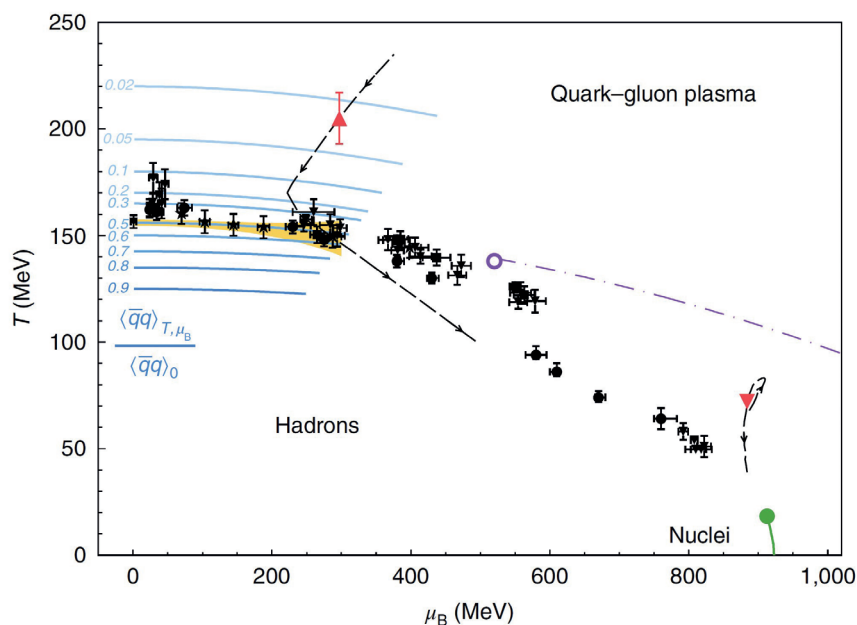


Figure 27. Sketch of the QCD phase diagram showing several landmarks obtained from experiments and lattice QCD calculations.

The HADES department is the host of the international HADES collaboration which operates the detector of the same name. HADES is one of two experiments in the Compressed Baryonic Matter pillar of FAIR, and is, with its large acceptance, optimized for heavy-ion experiments at a few GeV per nucleon beam energy. It is also operated with proton, deuteron and pions beams to address important aspects of hadron physics to provide an indispensable reference for the interpretation of the data obtained in the heavy-ion experiments. The HADES collaboration has strong contributions from the surrounding Universities in Darmstadt, Frankfurt and Gießen as well as from Wuppertal. Besides the GSI HADES department also the Nuclear Physics Department of Jülich is participating in HADES with emphasize on strange hyperon physics. While the latter program is carried out in the context of PANDA FAIR Phase-0 activities, the construction and operation of the RICH photon detector is the result of the CBM FAIR Phase-0 program. On the international level Russian, Polish, Czech, French and Portuguese institutes are members of HADES, with very strong contributions from the Jagiellonian University in Krakow and the Nuclear Research Center of the Czech Academy of Science. Recently also a group from Uppsala, Sweden joint the collaboration in view of the PANDA FAIR Phase-0 program.

The HADES department takes many responsibilities in the operation of the HADES detectors, both concerning the spectrometer as well as in the data analysis. Among such responsibilities for detector systems are the drift chambers MDC (together with Goethe University Frankfurt, JINR Dubna), the electromagnetic calorimeter ECAL (together with TU Darmstadt, INP of CAS Rez, Jagiellonian University Krakow) and the ring-imaging Cherenkov detector RICH (together with Liebig University Gießen and Bergische University Wuppertal), time zero detector for timing precision and beam monitoring (GSI, TU Darmstadt, GU Frankfurt). The Experiment Electronics and HADES departments are also strongly involved in the development and production of read-out electronic with emphasis on implementing digitizers in FPGAs (in collaboration with Goethe University Frankfurt). This development is also of importance for FAIR detector systems currently under construction. The HADES department also maintains and develops the analysis framework and organizes the reconstruction and simulation runs on the Green IT Cube.

The goal of HADES research is to determine the properties of baryonic matter at the highest baryon-chemical potential accessible in heavy-ion collisions. This activity is part of the world-wide quest for the structure of the QCD phase diagram and the properties of QCD matter under different conditions of temperature and pressure (see Figure 27). HADES is in particular specialized on the detection of virtual photon radiation out of the hot and dense phase of the reaction. By means of that probe, direct information on the temperature and properties of vector mesons in the medium can be obtained. Complementary information is encoded in the production of hadron carrying strangeness as respective hadron cannot be produced in a single nucleon-nucleon collision at such energies. The yields and spectral distributions of strange hadrons therefore provide insight in the degree of collectivity eminent to the production process. These and many more observables measured with HADES at beam energies as provided by SIS18 provide an important benchmark for the so-called beam energy scan which will connect the observation made here with the ones made at collider energies (e.g. ALICE).

A particular aspect of the HADES program is the hadron physics program using proton and pion beams. Indeed, the combination of a secondary pion beam with a dilepton spectrometer of large acceptance is world-wide unique.

## Highlights in 2019

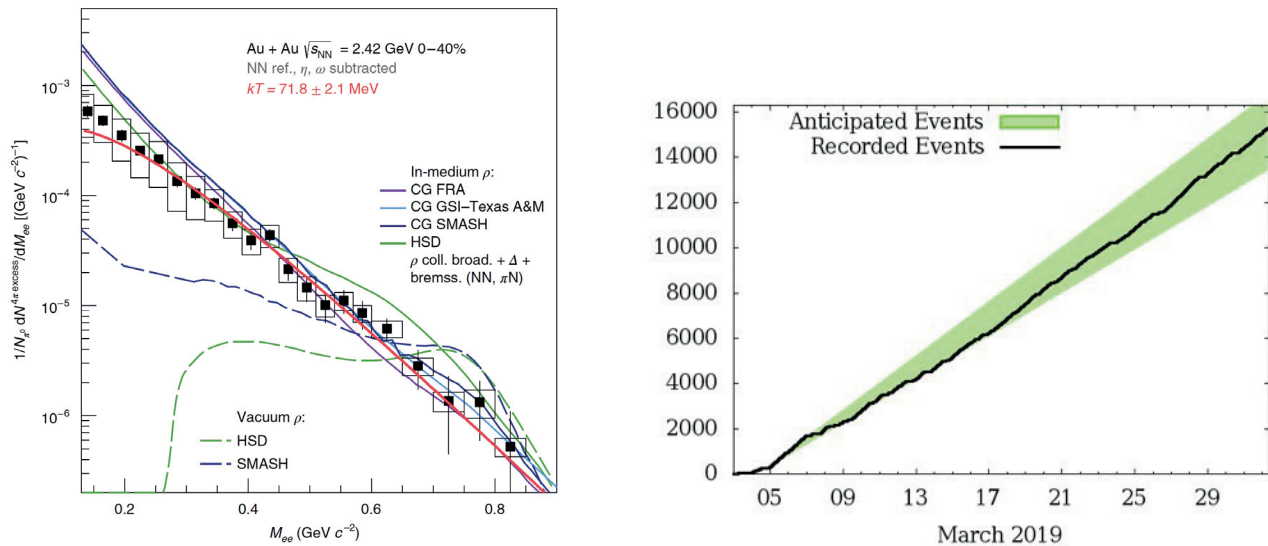


Figure 28. (Left panel) Continuum dilepton radiation extracted from Au+Au collisions. The data is compared to various model calculations: (right panel) Performance plot showing the number of collected events over the beam time. The various kinks reflect downtimes due to beam sharing or failures. The green band depicts the planned corridor.

For the first time electromagnetic continuum radiation could be extracted for a large collisions system at SIS18 beam energies. This radiation is emitted through the evolution of the dense and hot matter formed in the collision. To extract this radiation, not only a high combinatorial background due to chance combinations of electrons and positrons not originating from one and the same virtual photon but also contributions from the early and late stages of the reaction have to be thoroughly determined and subtracted. The contributions from the early stage are derived from measurements of dilepton production in proton and deuteron scattering of a proton target. Figure 28 (left panel) shows the final result which is obtained for the 40% most central collisions of Au+Au at 1.23 A GeV and was found to outshine the other contributions by a factor of eight. The most striking findings is the near exponential slope which is interpreted as due to a strong melting of the  $\rho$  meson which acts as a mediator between the baryonic medium and the dileptons. Because of this feature, which indicates a very strong medium effect, enabled the extraction of the mean temperature of the emitting source by simply adjusting a Planck distribution function to the data. The result has been published in 2019 in Nature Physics.

Another surprising observation was made while studying pion-induced strangeness production of nuclei. Comparing the  $K^-/K^+$  multiplicity ratios for a heavy (W) and a light nucleus (C), evidence for a sizeable  $K^-$  absorption was found. Also  $\Phi$  mesons could be reconstructed, although with less statistics. Yet, also for the case of the data supports substantial absorption effects.

### The first FAIR Phase-0 production run

Another highlight of 2019 was the very successful data taking for the collision system Ag+Ag. The run was taking place in March and lasted for about four weeks. It was the first production run in the FAIR Phase-0 campaign with the new controls system for the UNILAC and SIS18 accelerator in place. With the usual parallel operation in place, HADES was able to collect a total of 15 Billion events amounting to about half a PByte of data. The run was very stable, and the data could be analysed in real time on the Green Cube. Both, the new RICH detector and the ECAL with four sectors equipped with lead glass modules were used in the beamtime.

### Outlook for 2020

In 2020, the main focus in the detector activities is the installation of the new forward detectors. This detector system will be placed in the field free region of the spectrometer covering polar angles between 0.5 and 7 degrees. It will thus instrument an important solid angle, so far not covered, for the detection of scattered protons in hyperon production experiments using proton beams. The detector system is in particular needed to conduct the research program on hyperon electromagnetic transition form factors (PANDA Phase-0). It consists of two double layers of straw trackers developed for the PANDA forward Straw Tracking Station. Behind these stations, a new RPC based time-of-flight wall will be placed. In combination, protons can be identified and their momentum measured with a precision of about 5 %.

Another major activity is the analysis of the Ag+Ag data. A first production of data summary tapes has been accomplished already in 2019, but meanwhile refined calibration parameters are available which are mandatory for the reconstruction of the rare probes.

### Selected publications of 2019

- Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al. (HADES Collaboration): Probing dense baryon-rich matter with virtual photons. *Nature physics* 15(10), 1040 - 1045 (2019) DOI:10.1038/s41567-019-0583-8
- Adamczewski-Musch, J. ; Arnold, O. ; Atomssa, E. T. ; et al. (HADES Collaboration): Strong Absorption of Hadrons with Hidden and Open Strangeness in Nuclear Matter. *Physical review letters* 123(2), 022002 (2019) DOI:10.1103/PhysRevLett.123.022002
- Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C.; et al. (HADES Collaboration): Sub-threshold production of  $K_0^*$  mesons and hyperons in Au+Au collisions at  $\sqrt{s_{NN}} = 2.4$  GeV. *Physics letters / B* 793, 457 - 463 (2019) DOI:10.1016/j.physletb.2019.03.065



## 4. Research of the NUSTAR departments

Coordination: Prof. Dr. Christoph Scheidenberger, Justus-Liebig-Universität Gießen & GSI  
Authors: Prof. Dr. Thomas Aumann, Prof. Dr. Michael Block, Prof. Christoph E. Düllmann, Dr. Jürgen Gerl, Prof. Dr. Christoph Scheidenberger

The NUSTAR Collaboration of GSI-FAIR aims at experimental and theoretical nuclear structure research, nuclear astrophysics and reaction studies, and superheavy element research. Presently, the NUSTAR Collaboration has more than 800 registered members from more than 100 institutions in 40 countries. Its main research instruments and experimental areas at GSI are located at SHIP/SHIPTRAP, TASCA, FRS, ESR and R<sup>3</sup>B in Cave-C. The respective research groups of GSI and HIM (Helmholtz-Institut Mainz) are integral part of the NUSTAR Collaboration and participate in and contribute, often in a leading role, to experiments with exotic nuclei at GSI. The NUSTAR Collaboration supports the development and construction of the Super-FRS, which is the central device of the collaboration at FAIR.

Considerable progress is apparent in the development and realization of NUSTAR detector setups and their associated infrastructure, both for FAIR Phase-0 and FAIR Day-1. The major activity in the year 2019 was the planning and preparation of the FAIR Phase-0 program. First experiments have been performed in 2019 at the UNILAC for the superheavy element program (in close collaboration with the Helmholtz-Institut Mainz), as well as in Cave-C, where the commissioning and two experiments at R<sup>3</sup>B took place with primary beams. Also the FRS was commissioned in fall 2019, controlled with the newly implemented accelerator control software LSA for FAIR. The experimental program is expected to start fully in year 2020 with several beamtimes at SIS18. This will allow the collaboration to obtain important and unique science results, to commission and test the new equipment and complex detector systems, and to train doctoral students and young researchers on the way to NUSTAR@FAIR. Already now, several new NUSTAR detectors (or at least major subsystems of them) are available and in test and/or use at GSI (e.g. R<sup>3</sup>B in Cave-C, the Super-FRS Ion Catcher prototype and the DESPEC FATIMA-AIDA setup at the FRS). The NUSTAR strategy for the coming years aims at the exploitation of new opportunities and a continuous transition from GSI to FAIR as soon as the Super-FRS becomes available. The research activities, which will be presented in the following, have been achieved in close collaboration of the NUSTAR departments with many scientists from all over the world in the framework of the NUSTAR Collaboration.

## 4.1 Department FRS/SFRS

Head: Prof. Dr. Christoph Scheidenberger, Justus-Liebig-Universität Gießen & GSI  
 Author: Dr. Timo Dickel, GSI, and Dr. Yvonne Leifels, GSI

The department FRS/SFRS Experiments is responsible for the maintenance and operation of the fragment separator at SIS18 and the development of new operation modi. In addition, the department staff operates several experimental stations at the FRS, in particular, the FRS ion catcher with a cryogenic stopping cell CSC for slowing down and thermalizing exotic nuclei, which have been produced and separate employing the FRS, and a multi-reflection time-of-flight mass spectrometer MR-TOF used to perform direct mass measurements and to provide an isobarically clean beam for further experiments, such as mass-selected decay spectroscopy.

### FRS maintenance and operation



Figure 29. Views into the FRS Top left: Upper Coil and vacuum chamber during repair. Middle and bottom left: target area and the first dipole after the repair without concrete shielding. Right: Second dipole after the repair, but before the reinstallation of the concrete shielding.

A short commissioning of the FRS was done in the beginning of April 2019. The third and the fourth dipoles of the FRS, which have been repaired in 2018, have successfully been tested with beam. The FRS standard detectors for beam monitoring, tracking, time-of-flight and energy loss measurements have been taken into operation and their signals have been closely inspected. The new control system based on the LHC Software architecture (LSA), which is also utilized for the GSI and FAIR accelerators, was tested and verified.

After the beam time, the first phase of the implementation of a modular exchange system for the components of the target chamber at the FRS was completed. This is the first step towards a remote control of the FRS target area, and is an important step to run the FRS at higher beam intensities.

Repair of the first two dipoles of the FRS has successfully been completed in summer 2019 and the FRS was commissioned in the November/December engineering run.

## WASA Installation

The WASA (Wide Area and Shower Apparatus) detectors and the superconducting solenoid magnet have been transported from Jülich to GSI. WASA is a large acceptance detector for neutral and charged particles, which was situated at the cooler synchrotron COSY and has been used in various experiments. The sub-detectors were already tested with cosmic rays, sources, and with proton beams. The tests with beam were done at COSY. Preparation for WASA experiments at FRS planned for 2021 are proceeding according to plans. WASA is a large-acceptance detector for charged and neutral particles.

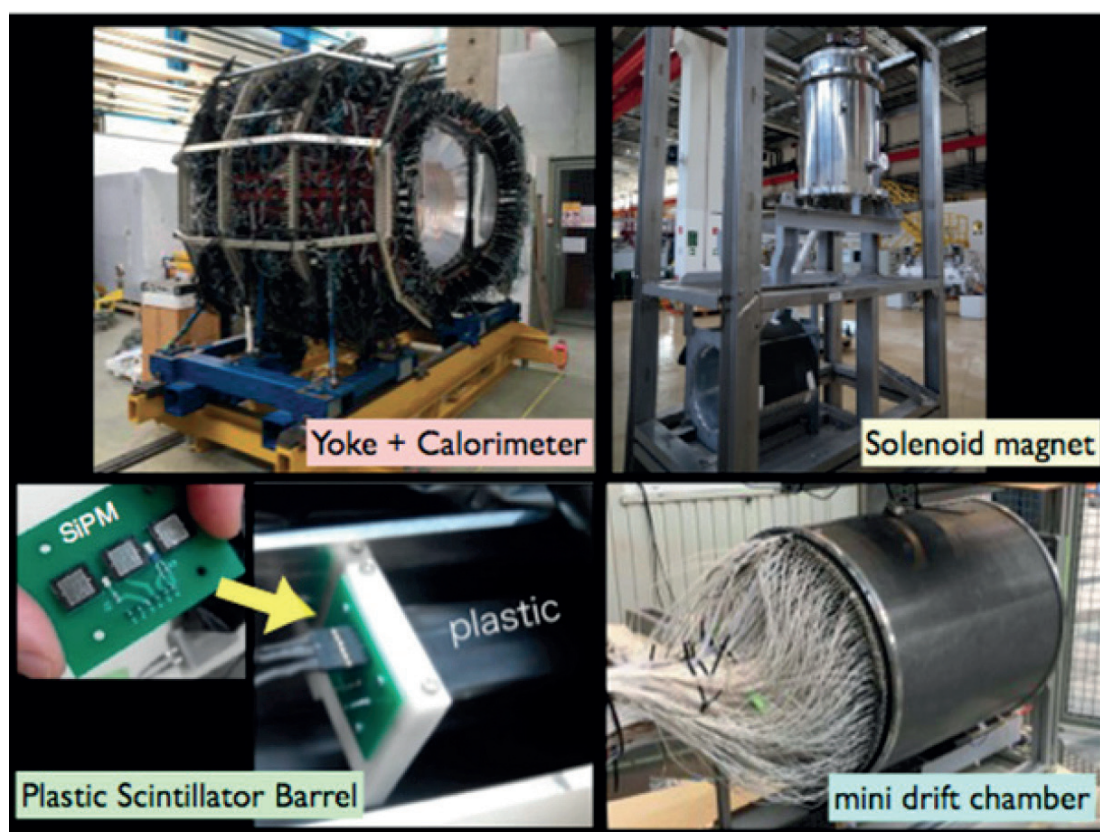


Figure 30. Different views of the WASA detector.

## Scientific highlights in 2019

A novel method for simultaneous measurement of masses, Q-values, isomer excitation energies, half-lives and decay branching ratios of exotic nuclei has been demonstrated [1]. The method is based on the idea to use a cryogenic stopping cell CSC as an ion trap. It could be demonstrated that storage times up to 10 s can be achieved. Fragments are produced in the target and are separated in-flight in the FRS. The nuclei of interest are stopped and stored in the CSC for a controllable duration. While the mother nuclei decay, almost all daughter nuclei are stored inside the CSC volume. The mother and daughter nuclides are consequently extracted to MR-TOF-MS, the multiple reflection time-of-flight mass spectrometer, where they were identified by their mass-to-

charge ratio and counted. This method was used to measure more than 30 short-lived isotopes in its ground and isomeric states, an accuracy of the mass measurements as low as  $6 \times 10^{-8}$  was achieved [2], which is unprecedented for time-of-flight mass spectrometers. This method requires high energetic beams in order to obtain a clean isotope separation and primary beams with a precise time structure. Therefore, FRS@SIS18 is the only facility where this method can be applied at the moment.

## Selected publications in 2019

- [1] Miskun, I. ; Dickel, T. ; Mardor, I. ; et al.: A novel method for the measurement of half-lives and decay branching ratios of exotic nuclei. *The European physical journal / A Hadrons and nuclei A* 55(9), 148 (2019) DOI:10.1140/epja/i2019-12837-8
- [2] Ayet San Andrés, S. ; Hornung, C. ; Ebert, J. ; et al.: High-resolution, accurate multiple-reflection time-of-flight mass spectrometry for short-lived, exotic nuclei of a few events in their ground and low-lying isomeric states. *Physical review / C covering nuclear physics* 99(6), 064313 (2019) DOI:10.1103/PhysRevC.99.064313

## 4.2 Department Nuclear Reactions

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

The department Nuclear Reactions develops and operates the R<sup>3</sup>B (Reactions with Relativistic Radioactive Beams) experiment, which allows for kinematically complete measurements of reactions with heavy-ion beams of typical energies 500 to 1000 MeV/nucleon. The scientific aim is to determine and understand the properties of neutron-proton asymmetric nuclei, the properties of astrophysical objects like neutron stars, as well as nucleosynthesis processes in stars, star explosions, and neutron-star mergers by measurements of reactions with short-lived nuclei.

A start version of the FAIR R<sup>3</sup>B experiment has been installed in Cave C at GSI while completion of the detector construction is still ongoing. For the commissioning and first FAIR Phase-0 production beamtime in 2019, the new super-conducting dipole magnet GLAD, as well as substantial fractions of the new detection systems developed and constructed for R<sup>3</sup>B at FAIR were in place and were brought into operation.

### Activities in 2019

The most important milestones for R<sup>3</sup>B in 2019 were the commissioning of the new equipment with beam, and the first two physics production runs. Since the FRS was not operated in 2019, production runs were limited to stable beams. The first experiment which has been performed in 2019 after the successful commissioning run with <sup>12</sup>C beam aims at constraining the symmetry-energy parameters, i.e., the equation of state for asymmetric nuclear matter, by an accurate measurement of total neutron-removal cross sections from neutron-rich nuclei. These cross sections are tightly correlated with the neutron-skin thickness of nuclei, and thus also tightly correlated with the density dependence of the symmetry energy  $E_{\text{sym}}(\rho)$  and  $L$ , i.e., the neutron pressure close to saturation density, as has been recently demonstrated in a theoretical study (T. Aumann et al., Phys. Rev. Lett. 119 (2017) 262501). Cross sections will be measured at different beam energies along the tin isotopic chain starting from stable isotopes up to the doubly magic neutron-rich <sup>132</sup>Sn. As a first step, data were taken with a stable <sup>120</sup>Sn beam on carbon and CH<sub>2</sub> targets at several beam energies from 400 to 1000 MeV/nucleon. The data from this successful first run will serve as a benchmark for the reaction theory. In the future, measurements for the neutron-rich isotopes will be carried out to provide tight constraints on the neutron pressure and thus the Radius-to-Mass Relation of neutron stars.

The second experiment which has been carried out in 2019 is devoted to measure one of the most important reactions in nuclear astrophysics, the <sup>12</sup>C( $\alpha$ ,  $\gamma$ )<sup>16</sup>O reaction, which determines the <sup>12</sup>C/<sup>16</sup>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 their abundances. The challenge is to measure the cross section at very low center-of-mass kinetic energies  $E_{\text{CM}}$  where this reaction occurs in stars. At R<sup>3</sup>B, the inverse <sup>16</sup>O( $\gamma$ ,  $\alpha$ )<sup>12</sup>C reaction can be measured by electromagnetic excitation at relativistic beam energies. Because of the low cross section at small  $E_{\text{CM}}$ , this experiment has to be performed at high intensity beams. To cope with the high beam intensities necessary to carry out this ambitious measurement, a dedicated detection system has been developed and installed, which has demonstrated its capability in the 2019 run. Due to the technical difficulties with the spill structure of the high-intensity beam and the short beam-on-target time, the final goal of reaching down to  $E_{\text{CM}}=800$  keV, which none of the many previous experimental attempts has accomplished, could not be achieved in this first run.

## Highlights in 2019

The nucleus can be described in first order by independent single-particle motion of nucleons bound by a mean-field potential generated by all other nucleons. Pairing correlations among nucleons, which are considered in the shell model approach, cause a smearing out of the Fermi surface, which is observable as a fragmentation of the single-particle strength by few MeV around the Fermi surface. It is established from electron-induced knockout reactions with stable nuclei, however, that the integrated spectroscopic strength (spectroscopic factors) in that energy window corresponds to only 60 to 70% of the expectation of fully occupied shells. This depletion is understood by additional correlations not considered in the shell model, that is coupling to collective states (long-range correlations) and nucleon-nucleon short-range correlations (SRC), both accounting for half of the reduction, respectively. It is an open question, how these correlations effect the structure of strongly neutron-proton asymmetric nuclei.

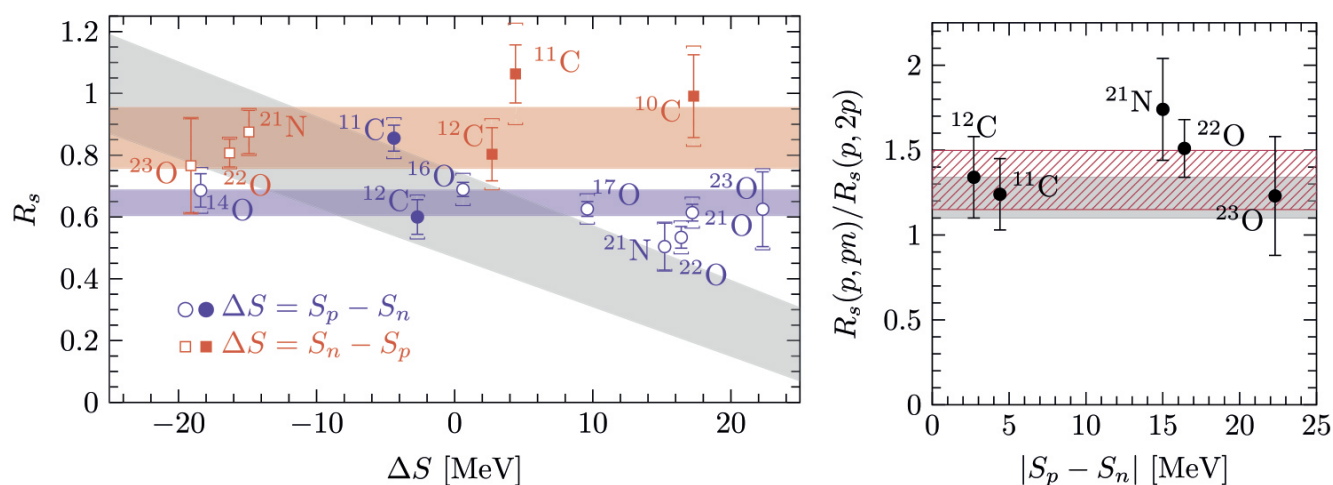


Figure 31. Left: Reduction of spectroscopic factors with respect to the expectations of full occupied shells as a function of neutron-proton asymmetry given in terms of the difference in nucleon binding energies  $\Delta S$ . Filled (open) symbols represent results from the present (previous) experiment [1], while the grey shaded area indicates the trend deduced from nucleon-removal reactions. The right panel shows the ratio of reduction factor for neutron and proton knockout for the isotopes where both cross sections have been measured. The hatched area indicates the average ratio with error band compared to a previous experiment for stable isotopes indicated by the grey band.

Recent experiments at JLAB have shown that SRC pairs are dominated by  $n$ - $p$  pairs in a momentum range of 300-400 MeV/ $c$ , which is understood as a consequence of the tensor-dominated nucleon-nucleon interaction in that momentum range. In a neutron-rich nucleus, this would lead to a situation where one would expect the protons to be in average more correlated than neutrons, and carrying as a consequence the major fraction of the kinetic energy. Another consequence would be a stronger reduction of the aforementioned single-particle spectroscopic factors for the more deeply bound rare nucleon species in asymmetric nuclei, which has been indeed found in a systematic study of single-nucleon removal reactions at energies of 50 to 100 MeV/nucleon. The observed trend, shown as grey band in Figure 31 turns out to be even much stronger than expected from the  $n$ - $p$  dominance of SRC pairs as mentioned above.

$R^3\text{B}$  measured cross sections for  $(p,2p)$  and  $(p,pn)$  quasi-free knockout reactions at high beam energy which is considered, besides electron-induced knockout, to provide the cleanest probe to study the single-particle structure of nuclei and nucleon-nucleon correlations. The measurements include carbon, nitrogen, and oxygen isotopes covering a wide range in asymmetry. The comparison to theoretical cross sections, based on eikonal reaction theory and mean-field single-particle densities as input, results in reduction factors  $R_s$  around 0.6 to 0.7 (see Figure 31). The  $R^3\text{B}$  data show no, or only a weak asymmetry dependence consistent with the result reported last year from the previous measurement (included in Figure 31 as open symbols).

The new measurement (filled symbols) include also neutron knockout data (red symbols), which show a similar trend as a function of  $\Delta S$ . However, the reduction factors are systematically higher than for proton-induced reactions. The right part of Figure 31 shows the ratio of reduction factors for neutron and proton knockout for the isotopes where both reactions have been measured. The surprising observation of around 30% higher values for neutrons is compared to a previous study with  $^{12}\text{C}$  (indicated by the grey band), which shows a similar but not understood relative enhancement of neutron knockout reactions. Further experimental and theoretical investigations are needed to clarify the origin of this effect.

### Proton knockout reactions from $^{12}\text{C}$

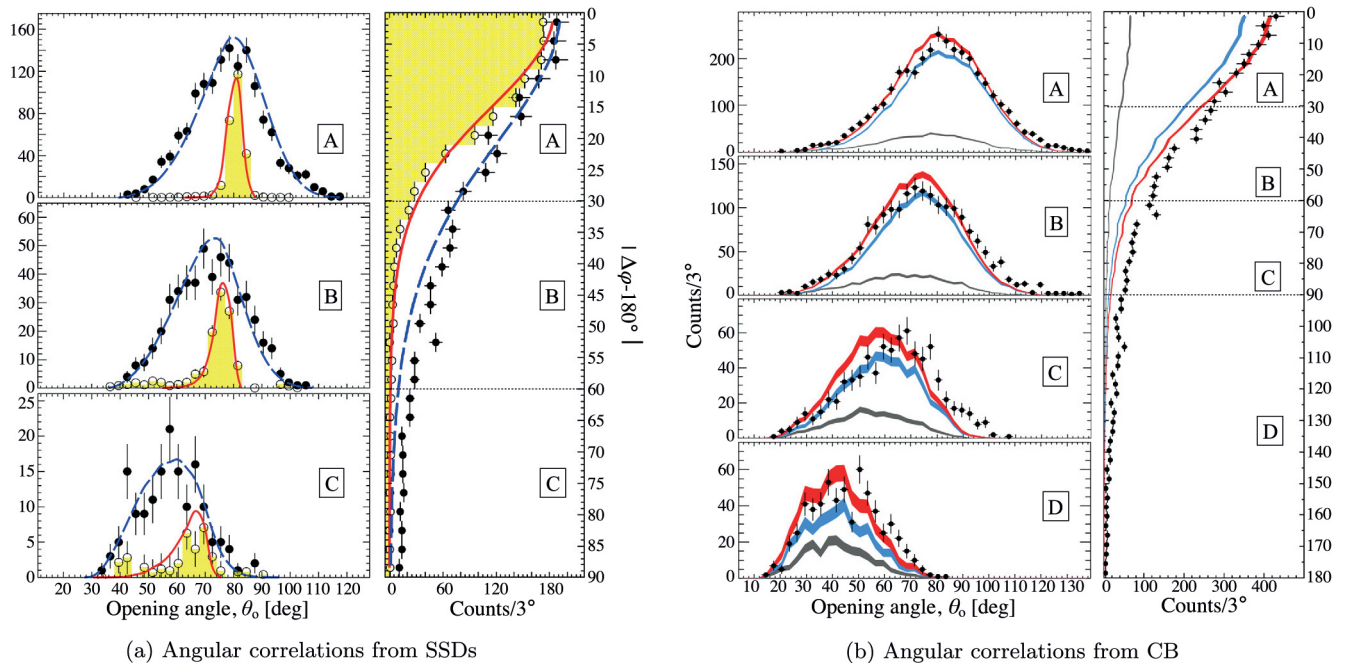


Figure 32. Two-particle angular correlations in coincidence with outgoing  $^{11}\text{B}$ . Fig. (a) displays the experimental (filled symbols) distributions of pp pairs measured with the silicon-strip (SSD) array compared to a previously measured distribution with a hydrogen target (yellow-filled area) for different intervals of  $\Delta\Phi$  as indicated in the right panel of (a). The left panel shows the opening angle between the two outgoing protons. Fig. (b) shows the same information deduced from the Crystal Ball only without information from the silicon array but for a wider range in  $\Delta\Phi$ .

The fact that the trend deduced from nucleon-removal reactions at energies around 100 MeV/nucleon is not seen in quasi-free knockout reactions might be related to a not fully understood reaction mechanism of the nucleon removal at lower beam energies. In order to gain deeper insight into the reaction mechanisms of nucleon knockout induced by nuclear targets like  $^9\text{Be}$  and  $^{12}\text{C}$ , previously taken data have been analyzed for the proton removal from  $^{12}\text{C}$  induced by  $^{12}\text{C}$  at 400 MeV/nucleon. A large fraction of this cross section stems from single nucleon-nucleon scattering events as could be identified by the present measurement [2]. The R<sup>3</sup>B setup was capable to detect besides the residual  $^{11}\text{B}$  fragment the two scattered nucleons in coincidence. Figure 32 displays the angular correlations between the two outgoing protons which shows the typical pattern for quasi-free scattering, i.e. in-plane scattering with an opening angle somewhat smaller than 90 degree (due to the nucleon binding and Fermi momentum). The distributions with carbon target are, however, significantly broader compared to quasi-free scattering with a hydrogen target (marked yellow in Figure 32). This difference can be quantitatively understood when considering the binding and Fermi momentum of both nucleons in projectile and target as indicated by the blue curve in the left part of Figure 32. This corroborates that these events, exhausting around 2/3 of the nucleon-removal reaction, indeed stem from single nucleon-nucleon collisions at these high energies.

It is interesting to note, that for around one third of the cross section only one proton is observed, without coincidence with a second scattered nucleon. A plausible interpretation of this result is that an outgoing nucleon after quasi-free scattering (QFS) is “lost” due to absorption in the target nucleus while the second nucleon freely escapes the interaction zone. Such a two-step mechanism is not considered in eikonal theories used to analyze nucleon-removal reactions, and it can result in additional reduction of the survival probability for  $(A-1)$  fragments. Since this effect is expected to be larger for well-bound nucleons compared to loosely bound nucleons (because of the different extension of single-particle densities), it could possibly give a sizeable contribution to the reduction of cross sections for knockout of more deeply bound nucleons as found in intermediate-energy nucleon-removal reactions compared to theoretical cross sections, which is not seen in quasi-free knockout reactions as discussed above. In the latter case, absorption of nucleons after QFS due to subsequent binary collisions are explicitly considered in the theory.

## Outlook for 2020

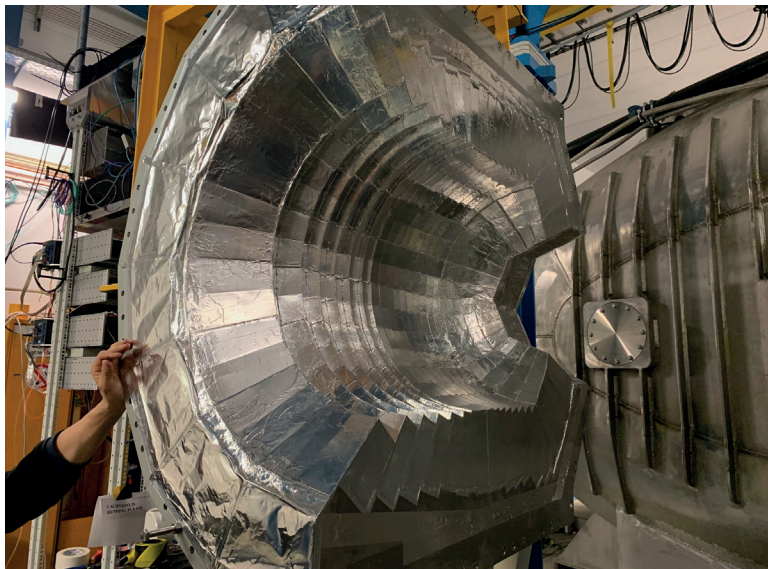


Figure 33. One half of the R<sup>3</sup>B photon and particle calorimeter CALIFA when it was mounted in the target area in front of the GLAD dipole magnet.

After the first experiments at R<sup>3</sup>B have been completed, the further upgrade of the experiment has been continued. A major addition is the CALIFA calorimeter surrounding the target for detection of photons and light particles. Figure 33 shows a photograph with one half of the detector when it was installed in front of the GLAD magnet. Although not yet equipped with all channels, the readiness of CALIFA will be an important improvement for the experimental program planned to be pursued in 2020.

Two type of experiments are foreseen to run in 2020. The first one will provide information on the shell structure of neutron-rich Ca isotopes by a measurement of quasi-free nucleon-knockout reactions.

The second campaign concentrates on the investigation of fission. Coulomb fission as well as for the first time quasi-free proton knockout induced fission will be measured. The latter reaction can provide the excitation energy of the fissioning system by a missing-mass analysis from the kinematics of the two scattered nucleons. Together with the coincident measurement of both mass- and charge-identified fission fragments, their angular and energy distributions, as well as accompanying neutrons, this measurement allows for the first time a complete characterization of the fission process as a function of excitation energy. The missing-mass measurement in the quasi-free proton knockout induced fission provides a tool to obtain information on the fission barrier of short-lived exotic nuclei. Besides the exciting perspectives this type of measurement provides

for obtaining nuclear-structure information on such nuclei, as well as for gaining detailed insight into the dynamics of the fission process, these measurements can provide a systematic evolution of fission barriers for neutron-rich nuclei, which is an important quantity to understand the fission recycling of elements in the r-process nucleosynthesis.

### Selected publications of 2019

- [1] Holl, M. ; Panin, V. ; Alvarez-Pol, H. ; et al.: Quasi-free neutron and proton knockout reactions from light nuclei in a wide neutron-to-proton asymmetry range. *Physics letters / B* B 795, 682 - 688 (2019) DOI:10.1016/j.physletb.2019.06.069
- [2] Panin, V. ; Holl, M. ; Taylor, J. T. ; et al.: Quasi-free proton knockout from  $^{12}\text{C}$  on carbon target at 398 MeV/u. *Physics letters / B* 797, 134802 (2019) DOI:10.1016/j.physletb.2019.134802
- [3] Aumann, T.: Low-energy dipole response of exotic nuclei. *The European physical journal / A* Hadrons and nuclei A 55(12), 234 (2019) DOI:10.1140/epja/i2019-12862-7

## 4.3 Department Nuclear Spectroscopy

Head: Dr. Jürgen Gerl, GSI  
Author: Dr. Jürgen Gerl, GSI

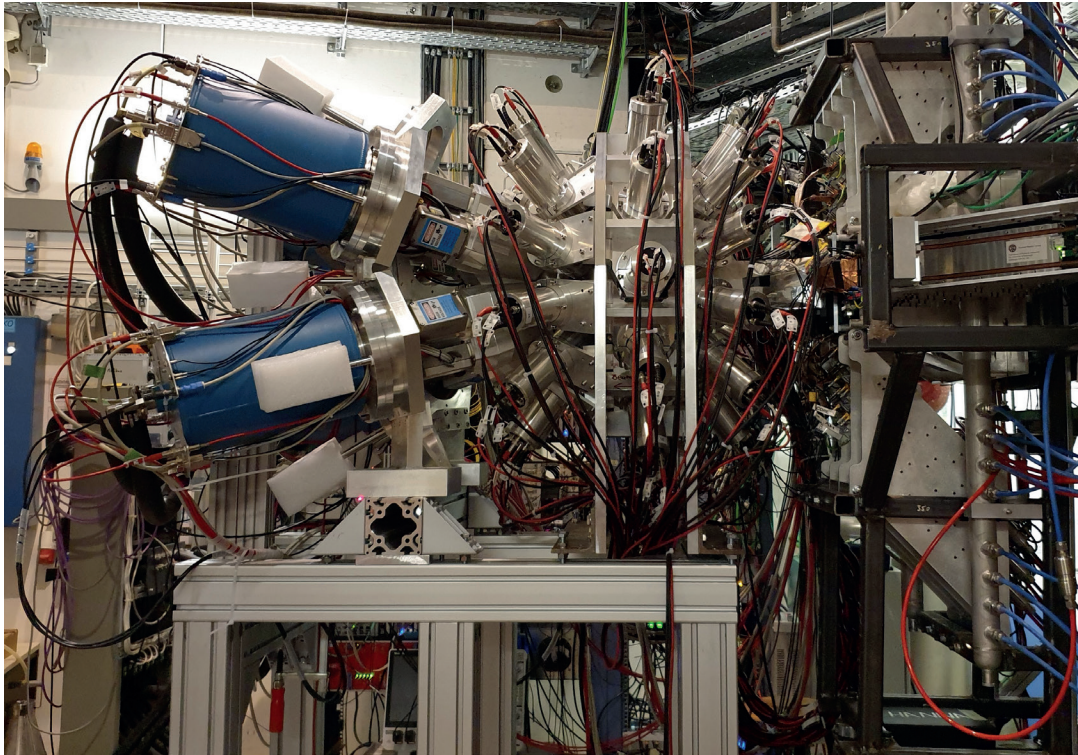


Figure 34. Experimental set-up with FATIMA, AIDA and DEGAS/GALILEO (Photo: J. Gerl).

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 ref [1]. 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 operates a special HISPEC/DESPEC set-up at the FRS and the group is coordinating the activities of the collaboration and developing and building the related infrastructure for the experimental campaigns at GSI and FAIR.

In the coming years the department will concentrate on decay studies employing DESPEC set-ups at the FRS within the NUSTAR FAIR Phase-0 campaign. These experiments will be complemented by investigations with stable beams at Coulomb barrier energies from the UNILAC accelerator, as well as by experiments at other international facilities.

## Activities in 2019

In 2019, the analysis of previous PRESPEC AGATA experiments was on going and important results, e.g. ref. [2], are continuously emerging. Complementing in-house activities, the group is performing experiments at other facilities, e.g. an experiment on  $^{84}\text{Mo}$  prompt spectroscopy was performed at JYFL, Jyväskylä, and studies on the structure of heavy Kr isotopes at Riken, Tokyo.

The major activities concentrated on the commissioning and optimization of the first DESPEC experiments within the NUSTAR FAIR Phase-0 campaign. The implementation of the so-called Fast Timing Setup was successfully completed on a movable platform at the S4 focal plane of the FRS. Figure 34 shows the detector arrangement including 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. All these independent sub-systems were coupled together by the White Rabbit time stamping system for the first time. In November/December 2019, the accelerator engineering runs were used to test the set-up with light and heavy fragments from the FRS. The analysis of the data confirmed essentially the performance parameters and revealed opportunities for further improvements. A sophisticated online/offline analysis system has been advanced considerably, making use of GSI's Green Cube computing farm.

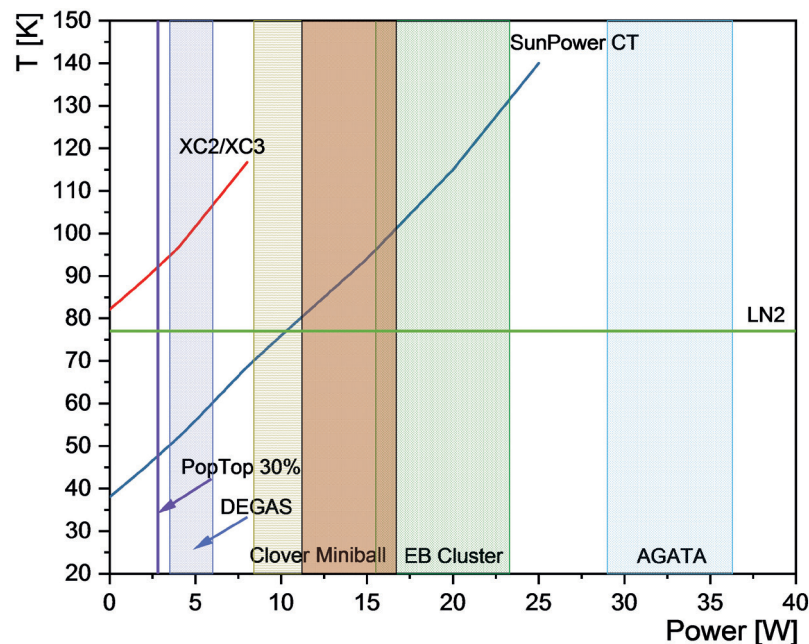


Figure 35. Cooling power consumption of DEGAS compared with other detector systems.

The most prominent detector research and development project, the DEGAS detector system including its active shielding [3] continued with the characterization of the first Ge triple prototype. The cryostat has minimal thermal losses and makes DEGAS superior to any other detector system as shown in Figure 35. Since the delivery of the commercial electrical cooler for DEGAS is severely delayed, a LN2 based cooling system with mini-dewars has been designed as an intermediate solution to get the DEGAS system ready for experiments.

## Technology Transfer

The VIDEO-2 gamma radiation localizing system employing six CeBr<sub>3</sub>(Tl) scintillator crystals has been finalized. Figure 36 shows the detector and a screen shot of the graphical user interface with an environmental background spectrum including the typical <sup>40</sup>K line (green line). The software (red lines) identified an “artificial” <sup>60</sup>Co source deployed in the test environment and determined its direction. This novelty has unprecedented sensitivity and a direction accuracy of <3 degrees, enabling the localization of enhanced gamma radiation by triangulation. It is intended for safety applications as well as for environmental monitoring.

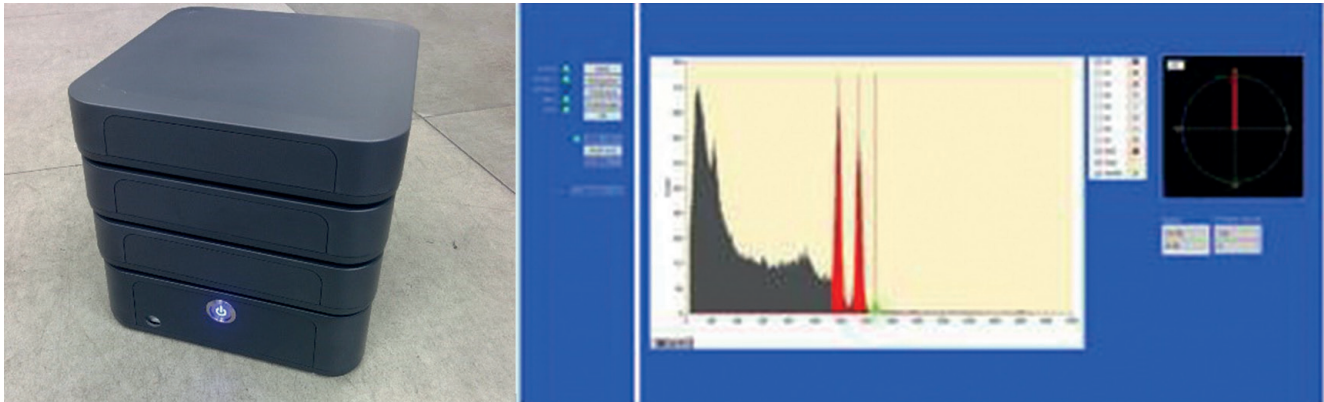


Figure 36. VIDEO-2 gamma radiation localizing system (left, photo J. Gerl) and associated GUI (right).

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## 4.4 SHE departments and HIM SHE section

Heads: Prof. Dr. Michael Block, Johannes Gutenberg-Universität Mainz, HIM Mainz & GSI, Prof. Dr. Christoph Emanuel Düllmann, Johannes Gutenberg-Universität Mainz, HIM Mainz & GSI  
 Authors: B. Andelic, HIM & RU Groningen; S. Boehland GSI & HIM & JGU; P. Chauveau, HIM & GSI; S. Chenmarev, HIM & GSI; P. Chhetri, HIM & GSI; F. Giacoppo, GSI & HIM; M. Götz, HIM & JGU & GSI; S. Götz, HIM & JGU & GSI; R. Haas, HIM & GSI & JGU; F.P. Heßberger, GSI & HIM; O. Kaleja, MPI-K Heidelberg & JGU & GSI; J. Khuyagbaatar, HIM & GSI; T. Kieck, HIM & GSI & JGU; S. Lohse, JGU & HIM; C.-C. Meyer, JGU & HIM; A.K. Mistry, GSI & HIM; S. Nothhelfer, HIM & GSI & JGU; V. Pershina, GSI; S. Raeder, GSI & HIM; D. Renisch, JGU & HIM; D. Rudolph, Lund U.; A. Yakushev, GSI

The SHE departments devoted to the research of superheavy elements, operate the recoil separators SHIP and TASCA and their ancillary installations including SHIPTRAP and a laser spectroscopy setup at SHIP as well as chemistry and nuclear spectroscopy setups at TASCA. In 2019, the activities at GSI focused on the UNILAC beamtime within the FAIR Phase-0 program and on the analysis of data obtained in prior beamtimes. At HIM, the advancement of actinide sample preparation, manipulation, and characterization for various applications was most central. In addition, technical developments, for example for single-ion mass measurements, have been performed.

### Synthesis/nuclear reactions

The six SHE with atomic numbers  $Z=107-112$  have been discovered in cold fusion reactions of heavy projectiles in the range of Cr-Zn with lead/bismuth targets. Cross sections to form SHE in cold fusion reactions decrease drastically with increasing  $Z$  of the compound nucleus. The dynamical mechanisms underlying this trend remained only partially understood. Experiments aiming at further elucidating cold fusion reaction cross section trends were carried out in collaborative work of the SHE Chemistry departments at GSI and HIM and the nuclear reactions group at the Australian National University (ANU), Canberra, Australia, at the Heavy Ion Accelerator Facility of ANU. The results [1] show that cold fusion reactions occur under a strong dynamical regime, disagreeing with a commonly held assumption that thermal-diffusion-like processes play a dominant role. This calls for microscopic approaches to describe this reaction step, hence stimulating further theoretical work.

Recently, complete fusion reactions involving proton emission during deexcitation of the compound nucleus have been suggested for production of SHE isotopes not accessible by neutron evaporation channels. At FLNR/JINR Dubna a cross section of 4 pb for the p-channel was measured at an excitation energy of  $E^* = 29$  MeV in bombardments of  $^{209}\text{Bi}$  with  $^{50}\text{Ti}$  [2]. At SHIP the maximum of that channel was observed at lower energy  $E^* = 21$  MeV in a first experiment in 1985 [3]. This observation was confirmed by a reanalysis of all irradiations of  $^{209}\text{Bi}$  with  $^{50}\text{Ti}$  performed at SHIP from 1997 to 2014 that resulted in a cross section maximum of  $18 \pm 8$  pb at  $E^* = 21$  MeV for the exotic p – deexcitation channel [4].

### Nuclear structure studies

Motivated by the quest for a magic proton number  $Z = 114$  (flerovium Fl) and the search for even- $Z$  odd- $N$  experimental anchor points relevant for nuclear structure theory in the superheavy element regime, a first attempt was conducted to explore the nuclear reactions  $^{48}\text{Ca}+^{242}\text{Pu}$  and  $^{48}\text{Ca}+^{244}\text{Pu}$  using high-resolution alpha-photon coincidence spectroscopy along  $^{287,289}\text{Fl}$  decay chains behind the gas-filled separator TASCA. The upgraded TASISpec decay station, contributed from Lund University, Sweden, was used, employing new dedicated Compex germanium detector modules [5] financed by the Knut and Alice Wallenberg foundation. First, the reaction  $^{48}\text{Ca}+^{206,207}\text{Pb}$  served to verify experimental parameters like the TASCA transmission and target-segment to  $\alpha$ -decay correlations. Short-lived nuclei were produced via  $^{48}\text{Ca}+^{\text{nat}}\text{Hf}$  to investigate pile-up events [6].

The set-up was found working flawlessly during the main experiment. The first 12 of the approved 25 days were scheduled in 2019; a reduced available beam-intensity led to the collected beam integral being equivalent to only about 6-7 effective days. Nevertheless, nine FI decay chains were identified, corresponding to a production cross section of approximately 10 pb, a value which is in agreement with literature.

In further TASCA experiments, the sampling ADC “FEBEX” modules developed by the GSI’s Experiment Electronics department have been extensively employed, e.g., to detect conversion electrons from the deexcitation of isomeric states, e.g., in  $^{254,255}\text{Rf}$  [7]. This demonstrates the potential of fast digital electronics for measurements of isomeric states in the heaviest nuclei, which can only be produced in small quantities. The technique also aided in studies of the two known short-lived fission activities associated with  $^{250}\text{No}$  - one of them has been assigned to a K-isomer - performed at the gas-filled recoil separator RITU at the University of Jyväskylä, Finland [8]. By observing conversion electrons preceding fission of one of those activities, the ground- and isomeric-state assignments could be made.

The probability of the electron capture delayed fission process (ECDF), which is known to occur in 29 nuclei with  $Z = 81-101$ , has so far not been described satisfactorily, especially in superheavy nuclei. A semi-empirical estimate of this process was developed, which accounts for all known cases [6]. The delayed fission appears to be strongly affected by the shape of the excited nucleus, in which the fission path towards scission is different than that of the nucleus in its ground state. In [6], semi-empirical predictions on the ECDF probabilities in odd-odd nuclei with  $79 < Z < 119$  are given. According to these estimates, beta-delayed fission decay modes appear to be among the main decay modes in superheavy nuclei which undergo beta decay.

The results of a detailed alpha-conversion electron-gamma spectroscopy study of  $^{258}\text{Db}$ , produced at SHIP in the  $^{209}\text{Bi}(^{50}\text{Ti}, 1n)^{258}\text{Db}$  reaction, and its  $\alpha$ -decay daughter products were published [10]. Two long-lived  $\alpha$ -decaying states in  $^{258}\text{Db}$  were observed and tentative spin-parity assignments were made for the ground state and the isomeric state, which was measured at an excitation energy of 51 keV. The  $\alpha$ -decay daughter isotope  $^{254}\text{Lr}$  displays a similar behavior. The isomeric level of this isotope was placed at 108 keV. Two long-lived  $\alpha$ -decaying states were observed in the granddaughter  $^{250}\text{Md}$ , also featuring an isomeric state positioned at an excitation energy of 123 keV. Partial, tentative level schemes for  $^{254}\text{Lr}$ ,  $^{250}\text{Md}$  and  $^{246}\text{Es}$  were proposed based on the  $\alpha$ - $\gamma$  coincidences.

Neutron deficient U, Pa, and Np isotopes with neutron numbers around  $N = 126$  were investigated at SHIP using the COMPASS detector setup [8]. Studying the decay of these often short-lived isotopes benefits from the use of fast digital electronics. Besides improved data on decay properties, the cross sections for the production of these isotopes with  $^{48}\text{Ca}$  were determined, showing that  $^{48}\text{Ca}$  does not provide an advantage as a projectile to access this region of the nuclear chart.

## Nuclear properties from laser spectroscopy

The laser spectroscopy experiments at SHIP were extended to  $^{255}\text{No}$ . The isotope shift and the hyperfine splitting of the  $^1S_1$ - $^1P_1$  transition were measured employing the RADRIS method established in pioneering experiments on  $^{252-254}\text{No}$ .  $^{255}\text{No}$  was produced via the electron capture decay of  $^{255}\text{Lr}$  with a yield of about 0.05 atoms per second. This production method was necessary due to the close-lying alpha energies of  $^{254}\text{No}$  and  $^{255}\text{No}$  that prevented an unambiguous identification in a direct production. Despite the low yield a fully resolved hyperfine spectrum of  $^{255}\text{No}$  was obtained confirming a nuclear spin of  $\frac{1}{2}$ . The data is still under analysis and will provide the magnetic moment of  $^{255}\text{No}$ . The mean-square charge radius derived from the isotope shift extends the systematics in the nobelium isotope chain beyond the  $N=152$  shell closure. The achieved sensitivity opens the door for future experiments on Lr ( $Z=103$ ) for which preparatory studies identifying the optimum filament material for efficient desorption were carried out [12].

The accurate determination of nuclear properties by hyperfine spectroscopy in heavy elements calls for a high spectral resolution. In the RADRIS technique, the buffer gas environment results in a Doppler broadening of few GHz. This prevents resolving individual hyperfine components in some cases. A new approach, in which atoms are extracted in a supersonic gas jet and then laser

ionized perpendicular to this jet, reduces the Doppler broadening by about one order of magnitude without sacrificing efficiency. At HIM, a novel setup was constructed in collaboration with KU Leuven to implement this method at GSI utilizing the filament technique successfully applied in nobelium laser spectroscopy [13]. The new method will extend the reach towards short-lived isotopes not accessible with the RADRIS technique. For example, it will facilitate a measurement of the magnetic moment of the K-isomer in  $^{254}\text{No}$  to unambiguously assign its nuclear configuration. The commissioning of the gas jet setup is ongoing and a first online test with  $^{155}\text{Yb}$  was completed in 2019.

The activities on the laser spectroscopy were complemented by an off-line measurement campaign on long-lived Es and Fm isotopes which became available in nano- and picogram quantities. Here, a first set of measurements allowed for a detailed investigation of the atomic structure of einsteinium.

### Nuclear properties from mass measurements

Several technical developments for extending the reach of high-precision mass measurements have been advanced. A new low-noise detection circuit based on a quartz resonator for the Fourier-Transform Ion-Cyclotron-Resonance (FT-ICR) detection technique has been implemented at TRIGA-TRAP [14]. The device is rather compact and relies on commercial quartzes that feature a high quality factor at room temperature. A proof-of-principle mass measurement on  $^{206,207}\text{Pb}$  ions was performed demonstrating a sensitivity on the order of tens of ions for room-temperature operation. The results are relevant for the design of tailored FT-ICR systems for SHIPTRAP and for the future MATS setup at FAIR.

Another novel detection technique for single-ion mass measurements with optical detection is being developed at the University of Granada within the TRAPSENSOR project [15]. An exotic ion of interest will be trapped in a laser-cooled ion crystal in a Penning trap. The sensor ion  $^{40}\text{Ca}$  was efficiently Doppler laser cooled in the strong magnetic field of a Penning trap using 12 laser beams. Once a two-ion crystal cooled to the (quantum mechanical) ground state has been realized, mass measurements can be performed applying quantum logic techniques.

For future off-line measurements of long-lived nuclides, the laser ablation ion source of SHIPTRAP has been improved by an optimized miniature radiofrequency quadrupole design. This will facilitate measurements with lower atom numbers on the order of  $10^{14}$  and below. The characterization and optimization of the cryogenic gas cell for SHIPTRAP was completed [16]. The improved performance enables future mass measurements of Rf and Db isotopes. The data analysis of the 2018 SHIPTRAP campaign was completed and systematic uncertainties to be considered in low-rate measurements with the phase-imaging technique were investigated. A publication is in preparation.

### Chemical properties

The evaluation of all available experimental data on the chemical interaction of Fl (element 114) with a gold surface has been finalized. A detailed analysis of a thin gold layer on a detector surface showed this surface to be inhomogeneous. An extended model for the interaction of Fl with such surfaces including the mobility of an adsorbed atom on the surface, was proposed. This model allows describing all available experimental data well and reveals that the strength of the interaction is decisively site-dependent. A publication detailing the chemical properties of Fl has been submitted.

Experimentally, the focus of experiments at GSI was on preparing and optimizing the experimental setup for the study of chemical properties of nihonium Nh (element 113). The first chemical study of Nh at TASCA was attempted in 2016. No Nh events were observed in a three-week experiment. Since then, several preparatory studies with the lighter homolog Tl as well as further model elements have been performed, aiming at a faster and more efficient extraction of short-lived and chemically reactive species into the gas chromatography and detection setup COMPACT. In the 2019 beamtime, reactive  $^{205-207}\text{Fr}$  was successfully extracted into a new miniaturized version

(miniCOMPACT), which was used in a combination with i) a modified recoil transfer chamber, and ii) with the former SHIP-TRAP gas buffer cell (BGC). Based on the results obtained especially with approach i), a four-week long Nh chemistry experiment is scheduled at GSI for 2020. The 2019 GSI experiments employing approach ii) proved that the combination of such a cell with the COMPACT setup is technically feasible. After first proof-of-principle experiments performed off-line using  $^{219}\text{Rn}$  ions and  $^{221}\text{Fr}$  ions from radioactive recoil ion sources, and a first beam-test performed at Texas A&M University in 2017, the main focus was on quantitatively confirming the extraction efficiencies achieved in off-line studies. The extraction efficiencies obtained off-line were confirmed by these experiments using the  $^{165}\text{Ho}(^{48}\text{Ca},\text{xn})^{213-\text{n}}\text{Fr}$ ,  $^{165}\text{Ho}(^{40}\text{Ar},\text{xn})^{205-\text{n}}\text{At}$ , and  $^{144,147}\text{Sm}(^{40}\text{Ar},\text{xn})^{187-\text{n}}\text{Hg}$  reactions, opening the prospects for chemistry experiments with very short-lived SHE isotopes beyond Fl. To overcome limitations of the current BGC, a novel design was worked out [17].

Studies of molecular chemical systems with SHE focused on further developments of the carbonyl chemical system, with the aim of a yield increase to open up perspectives to go beyond  $\text{Sg}(\text{CO})_6$ . A novel technique omitting the recoil separator step to spatially decouple recoil ion thermalization and gas phase chemical synthesis and replace it by a system comprising two separate, but directly coupled chambers for each of these steps has been developed. This was successfully tested with short-lived transition metal isotopes produced via  $^{235}\text{U}(\text{n},\text{f})$  at the research reactor TRIGA Mainz and via  $^{248}\text{Cm}(\text{sf})$ ; fission products, stopped inside a gas volume directly behind the target, were transported to a second, directly connected chamber. There, the products were either collected for direct counting to allow for yield measurements, or converted into volatile carbonyl complexes and transported to remote counting setups. Results from a beamtime conducted at the Tandem accelerator at JAEA Tokai, in which this approach was applied to 5d elements produced in  $^{19}\text{F}$  induced reactions were evaluated, and confirmed that the two-chamber approach indeed allows synthesizing carbonyl complexes of accelerator-produced single transition metal isotopes with higher overall efficiency than the previously used preseparator approach.

With the aim to support such gas-phase experiments on the volatility of Nh with respect to its homolog Tl, predictions of adsorption behaviour of group-13 hydroxides on a gold surface were made using periodic density functional theory (DFT) codes [18]. It was shown that  $\text{NhOH}$  should adsorb relatively well on gold, almost as strongly as elemental Nh. This similarity will render the identification of the chemical species difficult. Further work focused on the carbonyl chemical system. The program of the SHE section was supported by an extended visit of Professor M. Iliáš from Matej Bel University, Banská Bystrica, Slovakia via the HIM Fellow Program. With the aim to establish a chemical character of Lr upon adsorption of various surfaces of Ta, periodic ADF BAND calculations were performed for the Ta bulk and adsorption energies of Lu, Lr and Tl. Adsorption of Lr was shown to be similar to that of Lu, but different than that of Tl, showing Lr to be a good homolog of Lu. Its 6d and 7s atomic orbitals are involved in bonding. This was done in collaboration with JAEA Tokai, Japan, where preliminary experimental results for Lr were obtained; these agree very well with the calculations. With the aim to predict formation reactions of Mc and  $\text{Mc}^+$  in chemistry experiments, various formation reactions in the gas-phase were considered using the most accurate relativistic methods.

### Laser-produced protons inducing nuclear reactions at PHELIX

The first experiment on study of fission induced by laser-beam generated protons was conducted at PHELIX. Protons accelerated by a laser pulse, penetrated a Ti window and impinged on a 25- $\mu\text{m}$  thick U foil, inducing fission. Fission products recoiling from the foil were stopped in a gas-filled chamber. Using an inert-gas jet transport technique, volatile fission products (Xe and I isotopes) re-coiling were transported to a collector and identified via gamma spectroscopy. The SHE chemistry department contributed on the gas jet transport and identification aspects of this experiment.

### Tailor-made (actinide) samples

A main activity in Mainz is the production of tailor-made samples of (radio)isotopes for applications in basic chemical and physics research. These activities expanded into several areas.

Fundamental work to improve target production for SHE via the well-established “molecular plating” (MP) method was performed and novel electrochemical strategies were explored, not least to establish the capability to produce metallic layers that have a more favorable ratio of desired (=actinide) to undesired (=all other elements) atoms, even after oxidation, which occurs rapidly at air. The lanthanides and actinides are very electropositive elements. The metallic f-elements react with water to form hydrogen and metal hydroxides or oxides. Therefore, the pure metals cannot be deposited electrochemically from an aqueous solution. Nonetheless, in MP, the lanthanides and actinides are added in aqueous nitric acid. The incorporation of aqueous nitrates has several disadvantages, such as the gas development during the MP process. In f-metal chemistry, established alternatives to the nitrate salts include water-free tosylate or triflate salts. Both classes of substances can be easily synthesized and are adequately described in the literature. Initial tests with tosylate have already shown a significant improvement in thin-film quality.  $^{248}\text{Cm}$  targets produced by this method were successfully used in the muX-experiment at Paul-Scherrer Institute in Villigen, Switzerland, where conventional MP-targets have failed before. As a next step, irradiation test of triflate targets will be carried out at GSI to explore the suitability of such targets for heavy-ion research.

$^{233}\text{U}$  recoil ion sources providing the alpha-decay daughter  $^{229\text{m}}\text{Th}$ , which were prepared at HIM, were employed by collaboration partners at LMU Munich in experiments to determine the excitation energy of this exotic nuclear isomeric state. It is the by far lowest-lying known such state in any nucleus, located at an energy below 10 eV. Using the ground state  $^{229}\text{Th}$ , laser light provides sufficient energy to bridge these 10 eV, rendering the  $^{229\text{m}}\text{Th}$  system the only known case where laser techniques are applicable to manipulate a nuclear system. This is conjectured to provide the basis for a future “nuclear clock”, potentially outperforming the most precise current atomic clocks owing to the enhanced shielding of the oscillating system, i.e., the nucleus, by the electron shell. The excitation energy, though, has so far only been inferred indirectly. Using a retarding field electron spectrometer, the energy of electrons emitted in the deexcitation of the isomer to the ground state was measured, thus giving experimental information on the excitation energy, which is 8.28(17) eV, corresponding to a wavelength of 149.7(31) nm [19]. This paves the way for the development of suitable laser systems to determine the exact value of the excitation energy with a precision typical of laser-based approaches and is thus a milestone on the way to the nuclear clock. Scientists from LMU Munich, MPIK Heidelberg, TU Vienna, U. Bonn, GSI Darmstadt, HIM Mainz and JGU Mainz contributed to this achievement.

A multitude of further targets and sources, mostly of actinides were supplied as a contribution to collaborative work, including various  $^{229}\text{Th}$  and  $^{233}\text{U}$  sources for studies connected to  $^{229\text{m}}\text{Th}$ , e.g., for UCLA, CA; USA; JILA Boulder, CA, USA; Univ. Heidelberg, Germany; LMU Munich, Germany; PTB Braunschweig, Germany; Univ. Jyväskylä, Finland; as well as samples of Am, Cm, and Cf for SOREQ, Yavne, Israel, and for laser spectroscopy studies at Institute of Physics in Mainz.

### Trapping And sympathetic Cooling of Thorium Ions with Calcium (TACTiCa)

The TACTiCa Collaboration is working on thorium ion spectroscopy, especially of the  $^{229\text{m}}\text{Th}$  in a variety of charge states, for new insights in fundamental physics. The thorium ions will be loaded into a linear Paul trap and sympathetically cooled in a calcium-ion crystal. For a successful loading, the ions need to have a kinetic energy below 1 keV. In case of the  $^{229\text{(m)}}\text{Th}$ , the ions are produced by  $\alpha$  decay of  $^{233}\text{U}$  with a recoil energy of 84 keV. This kinetic energy is reduced by electrostatic deceleration to retain the initial charge state distribution of the Th ions. Furthermore, an ideal recoil ion source needs to be fabricated consisting of a single layer of uranium atoms to guarantee both, a high recoil efficiency and a negligible deceleration of the ions by interactions with the source material. Several fabrication methods were investigated for the potential of producing uranium monolayers. These include MP, Drop-on-Demand ink-jet printing, chelation by functionalized silicon surfaces and self-adsorption on thermally oxidized titanium foils. The  $\alpha$  spectra of sources produced by these methods were qualitatively characterized and compared with advanced alpha spectrometric simulations, to gain insights about the deposited source composition. The investigations lead to fabrication of high qualitative recoil ion sources. The design of the TACTiCa source section was finished [20], including IBSIMU ion flight simulations of the decelerated thorium recoil ions. The extraction efficiency is expected to be near to the geometric efficiency of about  $2 \times 10^{-5}$  and therefore a rate of about 1 ion/min is expected. The recoil ion source will be connected with a laser ablation ion source via an electrostatic quadrupole bender, therefore giving access to six iso-

topes of thorium for loading into the Paul trap. A Wien filter will be used to investigate the charge distribution of Th recoil ions and to select a specific charge state for loading into the Paul trap.

### An Offline Deposit Irradiation (ODIn) device at HIM Mainz

The ODIn pilot setup [21], comprising a sample irradiation position and two low-energy particle sources, i.e., an electron gun providing electron beams with energies of 10 eV up to 1.5 keV at currents in the 1 nA up to 100  $\mu$ A range, and a sputter ion gun based on microwave plasma discharge providing beams of gaseous elements at energies of up to 5 keV with currents up to 2 mA, was commissioned. This will serve to investigate to which extent it may be possible to perform the on-line baking-in process, traditionally tied to heavy-ion accelerator facilities, also at much smaller, accelerator-independent setups. For comparison MP produced lead targets were irradiated at ODIn and at TASCA (5 MeV/u  $^{48}\text{Ca}$ ;  $I=410^{12}$  Ion/s). They showed initially a similar chemical conversion from lead carbonate to lead(II) oxide. With increasing fluences, defect structures in the Raman spectrum could also be detected.

### International Year of the Periodic Table and TAN conference in Wilhelmshaven

2019 had been declared the International Year of the Periodic Table (IYPT) by the United Nations to celebrate the 150<sup>th</sup> anniversary. The SHE section / departments were involved in many activities related to IYPT. One highlight was a special symposium organized within the 6<sup>th</sup> international TAN conference (TAN 19), chaired by Ch.E. Düllmann and M. Block, with 125 participants from 19 countries. The symposium brought together members of the discovery teams of elements 112-118, including Peter Armbruster, Gottfried Münzenberg, and Yuri Oganessian.

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## 5. Research of the PANDA Departments

Coordination: Prof. Dr. Klaus Peters, Johann Wolfgang Goethe-Universität Frankfurt & GSI  
Author: Prof. Dr. 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 multi-purpose 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 in 2025. This involves overall and technical coordination and integration, core-software and trigger development as well as the full construction of the German in-kind DIRC for PANDA and several individual R&D and construction work packages connected to the Magnets, the Electromagnetic Calorimeter (EMC), Luminosity Detector (LMD), the Cluster-Jet Target, the experiment infrastructure and the Gas Electron Multiplier (GEM) detector. This is accompanied by Phase-0 activities like cooperation for the GlueX-DIRC at Jefferson Lab (Newport News, USA) and data analysis at GlueX and BESIII at IHEP (Beijing, VR China). In order to accomplish the goals, the department teams up inside GSI with the Electronics Lab, Detector Lab and the sections EMP and SPECF of the Helmholtz-Institut Mainz (reported elsewhere) and with the PANDA Coordinators at FAIR.

### Highlights in 2019

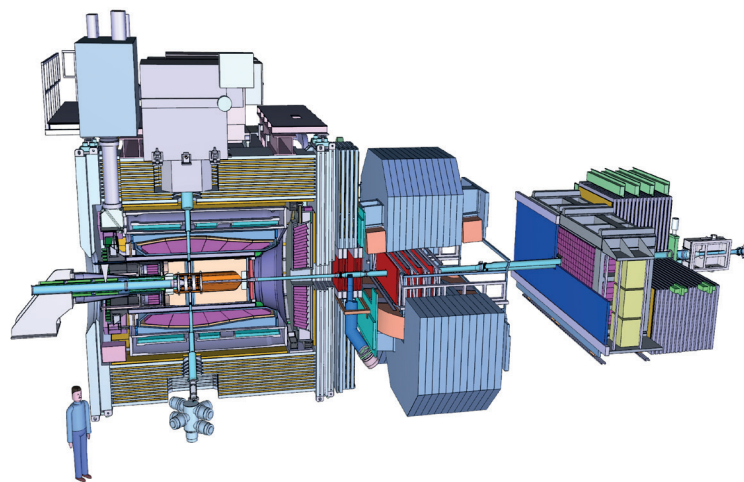


Figure 37. Set-up of PANDA.

The FAIR Day-1 setup of PANDA (Figure 37), which accounts for the available funding, production schedules and the needs of the early physics program, is under full construction. Core systems of the FAIR 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 place 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 forefront unique research, which has been vetted and scrutinized by the respective FAIR review committees.

Under the assumption that the starting luminosity at FAIR Day-1 could be significantly below design, the goal is to primarily concentrate on channels with large cross sections ( $\mu\text{b}$ ) and relatively simple event topologies. We expect to collect in the order of  $5 \text{ pb}^{-1}$  of data, which will be roughly 1% of the total FAIR Phase-1 integrated luminosity. Given these preconditions of Day-1, we have identified i) flagship experiments with a guaranteed physics outcome, ii) feasibility studies with a high discovery potential, and iii) development activities to realize the full physics program. These three categories of experiments will provide data for all pillars of PANDA. The focus will, to a large extent, be on studying the various production mechanisms of strange and partly charm-rich hadrons. In addition, we will map out the elastic antiproton-proton cross section for the ease of luminosity calibration at FAIR Day-1.



Figure 38. Sample coil winding with aluminium cables for the PANDA super-conducting magnet (left) and winding tool.

Another highlight is the completion of the yoke construction of the solenoid magnet. In addition, cooperation for the R&D of the manufacturing of the PANDA super-conductor with two Russian institutes, VNIIEP (Podolsk) and VNIINM (Bochvar) will produce the super-conducting cables with first tests of the extrusion method being very successful. Figure 38 shows the sample coil winding from aluminium and shows the winding tool.

Analysis wise, an important feasibility study has been published. Although being the first of the new charmonium-like states discovered since 2003, the nature of  $X(3872)$  is still one of the most puzzling research topics. In particular the width is unknown up to a rather loose upper limit of  $\Gamma_x < 1.2 \text{ MeV}/c^2$ , and the line shape of the resonance as the main indicator for the inner structure was not measured so far. Thus, accessing both the width and the line shape of the  $X(3872)$  with the capabilities of the HESR in combination with the PANDA detector has been investigated with a comprehensive simulation study, which at the same time serves as a general example to demonstrate the principle power of energy scan measurements at PANDA. The formation of the  $X(3872)$  resonance with a tuned anti-proton beam decaying to the known channel  $J/\psi\rho^0$  as well as background have been simulated and reconstructed with the GEANT-based PandaRoot framework to extract the expected efficiencies and resolutions. Given this information the energy scan with HESR was simulated for various accelerator and cross section scenarios and repeated many times to determine the expected sensitivities for a width and line shape measurement based on about three months of data taking. The results show that for a signal cross section of  $\sigma_x = 50 \text{ nb}$  the Breit-Wigner-like width of  $\Gamma_x \gtrsim 100 \text{ keV}/c^2$  will be accessible with significance of  $3\sigma_x$  in both considered accelerator modes with either high luminosity or high beam resolution.

## 5.1 Department Hadron Spectroscopy

Head: Prof. Dr. Klaus Peters, Johann Wolfgang Goethe-Universität Frankfurt & GSI  
 Author: Prof. Dr. Klaus Peters; Dr. Klaus Götzen, GSI

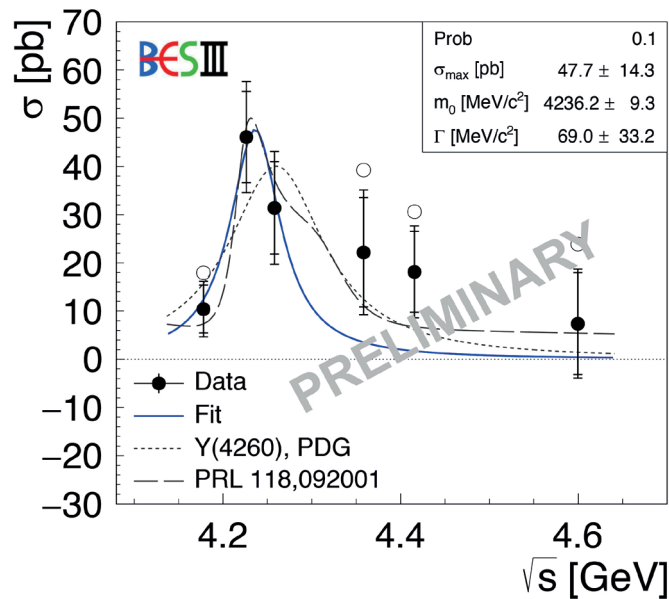


Figure 39. Invariant mass spectrum of the Y(4260).

Apart from analysis and construction work, a major task of the PANDA group at GSI is the management and organization of the PANDA Collaboration. The department leader is the Spokesperson of the PANDA Collaboration and also technical and resource coordination is done at GSI/FAIR. This implies the responsibility for the complete integration of the different sub-detectors, the necessary technical infrastructure, the finances, the scrutiny and review processes, and the reporting internally and to the respective authorities.

Among the many work packages, the group dealt with, the general installation concept and the infrastructure planning for PANDA is an important aspect and was detailed in 2019. A first installation Workshop took place in 2019. In future the concept of sharply defined installation windows will be replaced by a more parallel Lean Construction Management (LCM) with on-site management of daily, weekly and monthly work going on in parallel in the hall to maximize available concurrent installation time.

In addition, design work for the Central Space Frame (CSF) for the inner trackers and the beam-pipe and vacuum system in PANDA progressed in 2019. Specifications of the pipe along the beam axis, positioning of vacuum pumps and interfaces with detectors and target systems are in the planning phase and hardware prototypes are under way. Additional aspects involving the PANDA target are part of the R&D contract with the University Münster as well as the connection to the luminosity measurement together with the University Bochum.

Progress has been made as well in the reconstruction software for the particle tracking. Besides the evaluation of various algorithms for tracking in the forward spectrometer an overall Multi-Kalman feature was implemented. This option allows the track propagation for the different particle species individually with a Kalman-Filter technique and improves the overall precision of reconstructed track parameters like momentum and direction.

For the PANDA online event selection (software trigger) intensive studies have been carried out concerning the application of machine learning (ML) techniques. One aspect is the ranking and dimension-reduction of the input features. On the other hand various different ML concepts like Generative Adversarial Networks or Residual Neural Networks have been investigated to identify the most powerful and robust classification.

Concerning the analysis activities of the BESIII data, the focus lies now on unravelling the puzzling vector resonance  $Y(4260)$  by searching for new decay channels. Even though no evident  $Z_c$  state is found as intermediate resonance in final states, significant  $\eta_c$  production is found for  $\eta_c \pi^+ \pi^- \pi^0$ , and the energy dependent cross section is measured to be consistent with a production via the  $Y(4260)$  resonance (see Figure 39). Furthermore, investigations of possible  $Y(4260)$  decays to other charmonia as well as hyperon channels are carried out employing the inclusive reconstruction technique. The latter are in particular expected for the case the  $Y(4260)$  would be a conventional charmonium.

The analysis of the GlueX data has made significant progress. The search for the  $Y(2175)$  in reactions  $\gamma p \rightarrow \phi \pi^+ \pi^- p$  as a promising candidate for a strangeonium exotic, mainly discussed to be either a hybrid or a tetra-quark state is almost finished. Here, the  $\phi \pi^+ \pi^-$  cross section in photo production is addressed for the first time. The statistics of the GlueX Phase I data (2016-18) allows for a first measurement as function of beam energy and momentum transfer. Furthermore, upper limits on the photo production of  $\phi f_0$  and the exotic candidate  $Y(2170)$  are provided.

## 5.2 PANDA detector developments

Head: Dr. Joachim Schwiening, GSI  
 Author: Dr. Joachim Schwiening

The main objective of the department is the development and construction of solid-state Cherenkov Detectors, commonly 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 EIC detector (at BNL, USA).

GSI is the lead group for the PANDA Barrel DIRC detector, a German in-kind contribution to PANDA. The PANDA Barrel DIRC activities, performed in cooperation with the Universities of Erlangen and Gießen and the HI Mainz, focused in 2019 on the transition from design and R&D to construction.



Figure 40. 3 layer-spherical lenses for the PANDA Barrel DIRC.

A key element of the Barrel DIRC design is the innovative 3-layer spherical lens. Two optical companies, in Germany and the USA, were contracted to pre-qualify the vendors for mass production. Both companies successfully produced the technically challenging lenses. Figure 40 shows three 3-layer spherical lenses for the PANDA Barrel DIRC, made with a defocusing and focusing layer of lanthanum crown glass, placed between two layers of synthetic fused silica.

The calls for tender for the two items with the highest cost and longest lead-time started in winter of 2018/2019. Following extensive discussions with several qualified vendors, the contract was awarded in September 2019 to Nikon Corp, Japan. The call for tender for the Microchannel-Plate PMT sensors is at an advanced stage, with two vendors producing samples for a technical evaluation.

The readout electronics for the PANDA Barrel DIRC will be the DiRICH FEE system, developed by the Experiment Electronics department at GSI for the HADES/CBM RICH and the PANDA Barrel DIRC. A first version of a custom DiRICH backplane for the PANDA Barrel DIRC was produced in 2019. It was equipped with DiRICH power and data concentrator cards, as well as individual DiRICH cards, and installed in the DIRC lab at GSI (shown in Figure 41). An array of MCP-PMTs will be connected to this DiRICH test system and evaluated using a pico-second laser pulser to optimize the DiRICH design for PANDA.

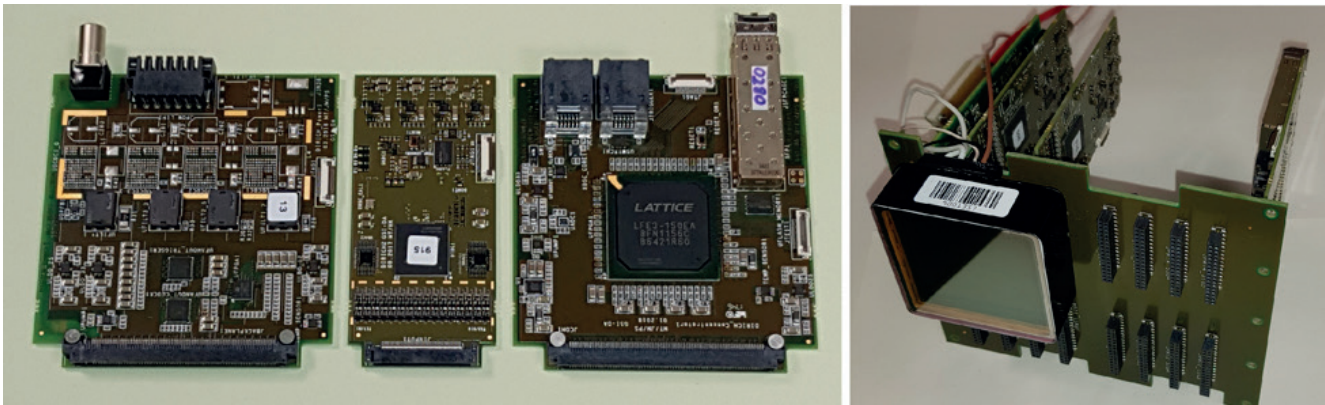


Figure 41. DiRICH power and concentrator cards.

GlueX experiment at Jefferson Lab was upgraded with a DIRC detector to significantly improve the particle identification (PID) capabilities and extend the physics reach for the high-luminosity GlueX-II run. The GlueX DIRC comprises four bar boxes from the decommissioned BaBar experiment, forming a forward PID wall (shown in Figure 42 left), equipped with new optics, photon detectors, and readout electronics. The PANDA DIRC team from GSI participated in the design, installation, 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 DIRC was installed into the GlueX detector and commissioned during two dedicated beam times in February and December 2019. The observed ring images and the measured Cherenkov angle resolution per photon obtained from the beam data (shown in Figure 42) are in good agreement with Geant simulations. Even at this early stage of the analysis, the DIRC detector has already improved the  $\pi/K$  separation in the forward region from 2 GeV/c to 3 GeV/c. More advanced alignment and calibrations, as well as optimized reconstruction algorithms, are expected to further improve the DIRC performance, providing valuable experience for the PANDA Barrel DIRC.

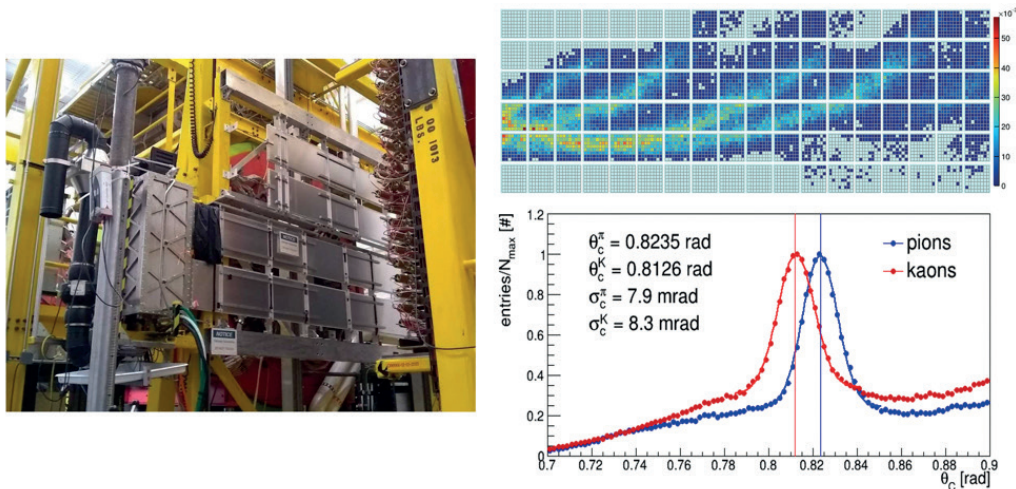


Figure 42. GlueX DIRC installed in the set-up at Jefferson Lab (left), particle resolution obtained (right upper panel) and pion/kaon resolution.

### Outlook for 2020

Major tasks towards the FAIR Day-1 configuration is the completion and submission of the last two TDRs for this initial setup. They comprise the data acquisition and trigger (DAQ) and the GEM detector. Also, final design reviews and follow-up of the magnet development and construction are important tasks for the PANDA groups. Also the experiment infrastructure will be detailed and presented to the respective committees for approval.

First spare modules of the LHCb tracker have arrived at GSI. Planning for refurbishment of the modules, a new framing, and interfacing of the electronics will be performed together with SLRI, Nakhon Ratchasima Thailand. Assembly will take place after enough elements have been shipped from CERN after a cooling-down period following the end of the latest LHC run.

Analysis will commence with large datasets in both experiments BESIII and GlueX. At GlueX in particular the new PID devices are in place for a better tagging of strange particles enabling a larger yield of interesting events. Within BES3 the data will be used to access new channels and thus to investigate the  $Y(4260)$  line-shape in various recoil channels using amplitude analysis eventually.

### Selected publications of 2019

- Ali, A. ; Amaryan, M. ; Anassontzis, E. G. ; et al.: First Measurement of Near-Threshold  $J/\psi$  Exclusive Photoproduction off the Proton. *Physical review letters* 123(7), 072001 (2019) DOI:10.1103/PhysRevLett.123.072001
- Ablikim, M. ; Achasov, M. N. ; Adlarson, P. ; et al.: Observation of  $e^+e^- \rightarrow \pi^+\pi^-(3770)$  and  $D_1(2420)0D^0+c.c.$  *Physical review / D* 100(3), 032005 (2019) DOI:10.1103/PhysRevD.100.032005
- PANDA collaboration ; Barucca, G. ; Davi, F. ; et al.: Precision resonance energy scans with the PANDA experiment at FAIR. *Zeitschrift für Physik <Berlin> / A Hadrons and nuclei A* 55(3), 42 (2019) DOI:10.1140/epja/i2019-12718-2
- Singh, B. ; Erni, W. ; Krusche, B. ; et al.: Technical design report for the PANDA Barrel DIRC detector. *Journal of physics / G* Nuclear and particle physics 46(4), 045001 (2019) DOI:10.1088/1361-6471/aade3d
- Etzelmüller, E. ; Schwiening, J. ; Ali, A. ; et al.: The PANDA DIRC Detectors. The 10th International Workshop on Ring Imaging Cherenkov Detectors, RICH2018, Moscow, Russia, 29 Jul 2018 - 4 Aug 2018 *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A* 952, 161790 (2020) DOI:10.1016/j.nima.2019.01.017



## 6. Research of the Theory department

Heads: Prof. Dr. Gabriel Martínez, Technische Universität Darmstadt & GSI

Author: Dr. Andreas Bauswein, Prof. Dr. Hannah Elfner, Prof. Dr. Gabriel Martínez

The Theory department consists of three groups: Hadrons and QCD lead by Matthias Lutz; Nuclear Astrophysics and Structure lead by Gabriel Martínez-Pinedo, and Transport and Experiment Simulation lead by Hannah Elfner. The following provides a summary of the research performed in 2019.

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.

In February 2019 an EMMI Workshop on “Probing dense baryonic matter with hadrons: Status and Perspective” with large international participation has been organized in close collaboration with the experimental colleagues at GSI. This has been a step towards preparations for the FAIR Day-1 Physics of CBM. Following the discussions at this workshop, there have been some technical advances like the implementation of a common HEPMC format into the SMASH and PHSD approaches. This is required to employ tools like RIVET that are developed to allow for easy comparison between theoretical calculations and experimental data from HEPData. In this context Christian Bierlich visited the group in Fall 2019 and a task force with ALICE and HADES collaboration members has been established to build an example analysis chain for experiment-theory comparison.

Photon production from the hadronic stage is a crucial ingredient to contribute to the solution of the so called photon puzzle, where the large yields and at the same time large elliptic flow measurements have not been understood so far. As a first step, microscopic photon production has been implemented in SMASH and was confirmed to match the expected thermal rates (Phys.Rev. D99 (2019) no.11, 114021). Another topic of high interest in the heavy-ion community concerns the formation of light nuclei in dense matter. The surprising finding that thermal models are able to describe the yields of weakly bound states of a few MeV with a temperature of  $\sim 150$  MeV has been explained within an afterburner calculation where SMASH is applied after a viscous hydrodynamic evolution. Due to the high cross-section for formation and destruction of deuterons in the hadronic phase, the chemical equilibrium yields are maintained throughout the whole evolution (Phys.Rev. C 99 (2019) no.4, 044907).

Within the PHSD approach the influence of finite chemical potentials on the partonic phase has been investigated in detail. All properties of the off-shell quarks and gluons have been extended to include the dependence on the chemical potential still ensuring the consistency with lattice results at zero chemical potential and finite temperature (Phys. Rev. C 100 (2019) no.1, 014911). No major effects on particle yields and spectra at several beam energies have been found so far.

Predictions for the Delta Baryon production in Au+Au collisions at 1.23 AGeV have been calculated within the UrQMD approach. Due to the inability of experiments to reconstruct resonances when the daughter particles have rescattered there is the expectation to observe a mass shift of around  $\sim 50$  MeV. The expected dependence on phase space properties has been explored in detail (J. Phys. G 46 (2019) no.10, 105107).

The main goal of the research in nuclear structure and nuclear astrophysics is to provide an accurate microscopic description of nuclear processes relevant for the evolution of stars and the nucleosynthesis of elements in the Universe. Particularly important is the evolution of nuclear structure far from stability which can impact the synthesis of heavy elements by the r-process. Another important area of research, that started in 2018 with the incorporation of Andreas Bauswein as leader of the ERC funded research area “Relativistic Astrophysics”, is the search for signatures of the high density nuclear equation of state on gravitational wave signals from binary neutron star mergers. Strong synergies exist with the CBM, NUSTAR and PANDA programs at FAIR.

The first observations of neutron star mergers by their gravitational wave signals highlight the possibility to learn about unknown properties of high-density matter in neutron stars from these events. In particular the gravitational wave signal may probe nuclear matter above saturation density and possibly deconfined quark matter in the non-perturbative regime of finite chemical potential but low temperature. In fact, it is currently unclear whether the hadron-quark phase transition occurs in neutron stars. Along these lines, a new unambiguous signature for the appearance of quark matter in neutron star mergers has been identified. This study is based on a large set of hydrodynamical simulations of neutron star mergers employing different equations of state to describe high-density matter [1]. It has been found that models with a phase transition to deconfined quark matter lead to a characteristic increase of the dominant gravitational-wave frequency of the postmerger remnant, which is initially strongly oscillating as a result of the very dynamical collision. When the two binary components merge, the density and temperature in the merger remnant increase. As a result a quark matter core can form in the center of the remnant even if original stars were purely hadronic. If a quark core forms, the equation of state of the stellar matter effectively softens and thus the remnant becomes more compact in comparison to a purely hadronic system. This compactification leads to a higher oscillation frequency. The study has estimated that such features are measurable with the current generation of ground-based gravitational-wave detectors or projected upgrades to these instruments. Interestingly, the work has also shown that such a detection can constrain the onset density of the hadron-quark phase transition.

The first observation of an electromagnetic transient associated to a gravitational wave signal from a binary neutron star merger provided first evidence of the operation of r-process nucleosynthesis in the material ejected during the merger. The transient evolved from blue to red during the first week providing evidence of the production of lanthanides. However, so far there is no evidence for the production of heavier elements. We have performed a study [2] aiming to determine fingerprints of heavy element nucleosynthesis in the kilonova electromagnetic signal. We have shown that kilonova light curves at time scales of weeks to months are dominated from the energy input of a discrete number of alpha decays,  $^{223}\text{Ra}$  and  $^{225}\text{Ac}$ , and the fission of  $^{254}\text{Cf}$ . Hence, future late time observations provide the potential to identify signatures of these individual isotopes, thus confirming the production of heavy nuclei in neutron star mergers.

Stars have different evolutionary paths depending on their mass. Low-mass stars such as the Sun will eventually become white dwarfs. Massive stars, on the other hand, finish with a spectacular explosion known as a supernova, leaving either a neutron star or a black hole behind. The fate of both low- and high-mass stars is well understood but the situation for intermediate-mass stars, with masses between seven and eleven times as much as the Sun, has remained unclear. These stars produce a degenerate Oxygen-Neon core whose evolution is regulated by how readily electrons are captured in the isotope  $^{20}\text{Ne}$ . In 2014, we realized that the electron capture rate on  $^{20}\text{Ne}$  is regulated by the then unknown second forbidden transition connecting the ground states of  $^{20}\text{Ne}$  and  $^{20}\text{F}$ . A experimental team lead by Oliver Kirsebom has measured a surprisingly large transition strength at the accelerator laboratory of the University of Jyväskylä. We have developed stellar evolution models based on the new rate that show that electron capture on  $^{20}\text{Ne}$  occurs at lower density than previously assumed. This favors a thermonuclear disruption of the star instead of a gravitational collapse to produce a neutron star [3]. Thanks to this measurement the rate of electron captures on  $^{20}\text{Ne}$  at stellar conditions is fully based on experimental information highlighting the potential of radioactive beam facilities like GSI/FAIR to determine astrophysical reaction rates. This work has been highlighted with a Viewpoint in Physics and in the arch 2020 issue of Physics Today.

## Selected publications of 2019

- [1] Bauswein, A. ; Bastian, N. F. ; Blaschke, D. B. ; et al.: Identifying a First-Order Phase Transition in Neutron-Star Mergers through Gravitational Waves. *Physical review letters* 122(6), 061102 (2019) DOI:10.1103/PhysRevLett.122.061102
- [2] Wu, M.-R. ; Barnes, J. ; Martinez Pinedo, G. ; et al.: Fingerprints of Heavy-Element Nucleosynthesis in the Late-Time Lightcurves of Kilonovae. *Physical review letters* 122(6), 062701 (2019) DOI:10.1103/PhysRevLett.122.062701
- [3] Kirsebom, O. S. ; Jones, S. ; Strömberg, D. F. ; et al.: Discovery of an Exceptionally Strong  $\alpha$ -Decay Transition of  $^{20}\text{F}$  and Implications for the Fate of Intermediate-Mass Stars. *Physical review letters* 123(26), 262701 (2019) DOI:10.1103/PhysRevLett.123.262701

## 7. Report of the ExtreMe Matter Institute EMMI

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

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

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

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

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

### EMMI Partner Institutions

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

### Rapid Reaction Task Force Meetings in 2019

*RRTF on Dynamics of critical fluctuations: theory - phenomenology - heavy-ion-collisions (April 2019)*  
This RRTF brought together experts from the field to discuss the experimental and theoretical status, challenges and perspectives of describing and measuring critical fluctuations in the dynamical environment of heavy-ion collisions and related physical systems. The goal was to make progress on questions that concern the proper treatment of the order parameter(s) in and out of the scaling region and the coupling of critical fluctuations to the dynamics of the non-critical bulk. The participants aimed at comparing details of the various approaches by different groups

and at identifying suitable observables. The results of the meeting are described in the article Bluhm, M. ; Kalweit, A. ; Nahrgang, M. ; et al.: Dynamics of critical fluctuations: Theory – phenomenology – heavy-ion collisions. Nuclear Physics A 1003, 122016 (2020) DOI:10.1016/j.nuclphysa.2020.122016 arxiv:2001.088319.

*RRTF on The space-time structure of jet quenching: theory and experiment (August 2019)*  
This RRTF explored the diagnostic power of the so-called Lund Diagram, as well as related versions of it, in constraining the space-time evolution of jet showers ploughing through the dynamically evolving fireballs of dense quark-gluon matter created in relativistic heavy-ion collisions. During the RRTF meeting, Lund-type phase space representations of a broad variety of jet shower evolution codes have been compared with each other, as well as with similar representations of available experimental data. The overarching goal of the RRTF was to bring together experts from diverse efforts world-wide working on similar problems.

*RRTF on LORandite EXperiment (LOREX) (December 2019)*  
This RRTF discussed the past, present and especially the future of the LOREX project. LOREX is the acronym of LORandite EXperiment, which addresses the long-time detection of solar neutrinos with the  $^{205}\text{Tl}$ -bearing mineral lorandite (TlAsS<sub>2</sub>) at the mine of Allchar, North Macedonia, via the neutrino-capture reaction  $^{205}\text{Tl} + \nu_e \rightarrow ^{205}\text{Pb} + e^-$ . LOREX is the only long-time geochemical solar neutrino experiment still actively pursued.

*RRTF on Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC (December 2019)*  
This RRTF scrutinized the theoretical and phenomenological description of quarkonium production in high-energy heavy-ion collisions, with the aim to distinguish between current approaches, narrow down uncertainties in the input parameters and set the path for future developments of reliable dynamical models of quarkonium transport. The overarching goal was to establish firm connections between heavy-quarkonium phenomenology in heavy-ion collisions and the microscopic properties of hot QCD matter.

## EMMI Events in 2019

- EMMI Workshop, "Central exclusive production at the LHC", Organizers: C. Ewerz, O. Nachtmann, R. Schicker, Feb 6, 2019, U Heidelberg
- EMMI Workshop, "Probing dense baryonic matter with hadrons: Status and Perspective", Organizers: A. Andronic, C. Blume, H. Elfner, M. Lorenz, Feb 11-13, 2019, GSI, Darmstadt
- EMMI Workshop, "Probing the Phase Structure of Strongly Interacting Matter: Theory and Experiment", Organizers: B. Friman, K. Redlich, V. Koch, N. Xu, Mar 25-29, 2019, GSI, Darmstadt
- EMMI Workshop, "Functional Methods in Strongly Correlated Systems", Organizers: J. Braun, M. Buballa, S. Flörchinger, J.M. Pawłowski, D. Rischke, B.-J. Schäfer, L. von Smekal, Mar 31 - Apr 6, 2019, Darmstädter Haus, Hirschegg, Austria
- EMMI Rapid Reaction Task Force, "Dynamics of critical fluctuations: theory – phenomenology – HIC", Organizers: M. Bluhm, A. Kalweit, M. Nahrgang, Apr 8-12, 2019, GSI, Darmstadt
- 17<sup>th</sup> Meeting of International Particle Physics Outreach Group IPPOG, Organizers: H. Beck, S. Goldfarb, B. Gulejova, C. Marcelloni De Oliveira, May 23-25, GSI, Darmstadt
- ECT\*-EMMI/GSI Workshop, "High-energy physics at ultra-cold temperatures", Organizers: G. Aarts, A. Bermudez Carballo, M. Lewenstein, June 10-14, 2019, ECT\*, Trento, Italy
- ECT\*-EMMI/GSI Workshop, "Simulating gravitation and cosmology in condensed matter and optical systems", Organizers: R. Balbinot, I. Carusotto, M. Rinaldi, R. Sturani, July 22-25, 2019, ECT\*, Trento, Italy
- EMMI Rapid Reaction Task Force, "The space-time structure of jet quenching: theory and experiment", Organizers: U. Heinz, P. Jacobs, K. Tywoniuk, U. Wiedemann, Aug 12-16, 2019, GSI, Darmstadt
- EMMI Physics Day 2019, Organizers: P. Braun-Munzinger, C. Ewerz, A. Schwenk, Nov 19, 2019, GSI, Darmstadt
- EMMI Workshop, "3<sup>rd</sup> workshop on anti-matter, hyper-matter and exotica production at the LHC", Organizers: S. Bufalino, B. Dönigus, K. Redlich, J. Schaffner-Bielich, L. Turko, Dec 2-6, 2019, U Wroclaw, Poland
- EMMI Rapid Reaction Task Force, "LORandite EXperiment (LOREX)", Organizers: Yu. Litvinov, M. Pavićević, T. Stöhlker, Dec 12-13, 2019, GSI, Darmstadt
- EMMI Rapid Reaction Task Force, "Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC", Organizers: A. Andronic, P.-B. Gossiaux, P. Petreczky, R. Rapp, M. Strickland, Dec 16-20, 2019, GSI, Darmstadt

## 8. Research in the Target Laboratory

Head: Dr. Bettina Lommel, GSI

Authors: Dr. Bettina Lommel, Elif Celik Ayik, Annett Hübner, Dr. Birgit Kindler, Jutta Steiner, Vera Yakusheva

After the commissioning of the refurbished laboratory at its new site, the target laboratory is again operational and prepared targets for experiments and source material for the accelerator.

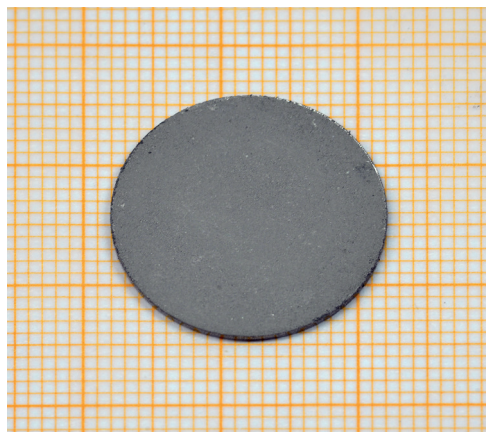


Figure 43.  $^{63}\text{Ni}$  Target for nuclear resonance fluorescence experiments to investigate low-spin excited modes such as the so-called Pygmy Dipole Resonance (Photo: G. Otto, GSI)



Figure 44. Starting material versus lapped and polished copper samples as part of the materials research test series, where the smoothest possible, pore-free surfaces are investigated, which ensure minimal adsorption and thus small desorption rates of residual gas particles in accelerator components (Photo: G. Otto, GSI)

In 2019, a 3D-laser-scanning microscope was purchased from Keyence and taken into operation. The new device was essential for characterizing target samples prepared for the plasma physics department. In addition, it was needed to characterize the surface quality of copper-plated radio frequency quadrupoles RFQ. The copper plating was done at the galvanic workshop of GSI, which was brought back to operation in 2019. In a first test, prototype RF quadrupoles of the p-Linac for FAIR have been copper-plated and the quality of the process was and will be measured and documented in the target laboratory.

We supported the NUSTAR collaboration e.g. for the heavy-element physics and chemistry group with numerous targets like different targets from enriched rare-earth materials, an example can be seen in Figure 43, that partly had to be chemically prepared in the wanted form or compound, respectively. We prepared titanium-backings for molecular plating at the Institute for Nuclear Chemistry at Mainz. Moreover, we characterized degrader parts for the fragment separator.

For the APPA collaborations, a lot of targets and coatings were prepared, mainly for plasma physics and material science. For example, more than 50 pieces titanium-wire with a diameter of 50  $\mu\text{m}$  were embedded, lapped and polished at the tip. Different preparation methods had to be tested and had to be documented. For understanding desorption and adsorption processes in the accelerator, samples were prepared in a wide variety of surface qualities, see Figure 44.

For the accelerator operation, we prepared carbon stripper foils for different positions, for example at the entrance to the transfer channel. For ion source operation,  $^{48}\text{Ca}$  was reduced from the carbonate to the metal, which is needed for UNILAC heavy ion beams 2020 for research on super-heavy elements.

The staff of the target laboratory also operates a radioactive laboratory, where targets from uranium metal,  $\text{UF}_4$  and  $\text{UO}_2$  for experiments at GSI and at other places worldwide are produced.

## 9. Research of the department Detector Laboratory

Head: Dr. Christian Schmidt, GSI  
Authors: Dr. Christian Schmidt

The detector laboratory has been engaged in a broad variety of projects.

For R<sup>3</sup>B the assembly process for single layer scintillating fiber tracking detectors was established. Hundreds of individual fibers of round as well as rectangular cross section may be assembled to thin mats of 50 cm x 50 cm active area. They can be read-out through multi anode photo multipliers MAPMT (Hamamatsu H9500 or H13700) in combination with the PADI front-end ASIC and a successive FPGA-based TDC, previously developed at GSI experiment electronics. Any fiber cross section with a diameter larger than 0,2mm can be handled. Sample prototypes were tested in a beam time at KVI (Groningen) and also employed in R<sup>3</sup>B FAIR Phase-0 physics experiments in 2019. Additionally, two much smaller prototypes were tested in an FRS beam time.

A time projection chamber, which can be used as an active target, was built and equipped with a complete electronic read-out chain. A beam time at University Mainz has been realized in which the resolution together with the energy threshold of the active target could be improved considerably with respect to earlier developments.

For R<sup>3</sup>B FAIR Phase-0 a series of silicon micro strip detectors were arranged around the newly installed hydrogen target. These detectors could for the first time be operated with active cooling in vacuum. Signal noise and energy resolution could be improved. The optimization of firmware resulted in a considerable improvement in rate capability of the readout electronics.

For the silicon tracking stations STS of the CBM experiment, the module assembly procedures for the silicon detector modules which comprise a double sided sensor with 2048 channels, up to 50cm long micro signal cables and the readout front end board, have been elaborated and brought to a viable state that allows to reliably estimate the micro mounting and assembly capacities needed for the CBM-STs. The preparations to large scale assembly may now embark.

The STS-XYTER ASIC, a dedicated ASIC development for CBM realized at the University of Science and Technology AGH in Krakow, has been brought to final production readiness. The detector laboratory was deeply involved in the characterization and validation of the design in close-to-final setups for the CBM-STs. In parallel, the detector laboratory has developed the 8-chip front-end board for the STS-modules which will be available in two different symmetries.

Along these activities, the detector laboratory organized for the second time a joint multi-project ASIC submission for CBM and other projects at GSI and for FAIR.

The detector laboratory together with the ALICE group and University Heidelberg also engaged in employing modern silicon CMOS pixel detectors, namely the ALICE ALPIDE sensor developed at CERN for the ALICE ITS2, in a test beam on heavy ions. To this end a 7-layer beam telescope provided by the CERN-Alice group was taken into operation. This cooperation allowed GSI to obtain first experience with the pixel device ALPIDE and the CERN-ALICE group to study the behavior of the device upon heavy ion irradiation.

Appreciable progress could also be achieved on the development of a Cherenkov detector setup as beam monitoring device. In order to improve timing resolution and with the goal to liberate such a system from any particular choice of active medium, a new modular time of flight detector (TOF) was constructed. The overall diameter of the setup measures 560 mm while the diameter of the liquid filled cuvette that serves as active Cherenkov medium is 18mm. Cherenkov photons are registered by 14 photo multipliers. The principle of measurement as well as the new data acquisition based on a FPGA-TDC on a VME board. The VFTX-TDC has been developed by the experiment electronics laboratory. The new DAQ was validated and tested in a FAIR Phase-0 beam time using

$^{208}\text{Pb}$ -ions at the FRS. The registered signal time distribution was compared to the one extracted from plastic scintillators that were mounted up- and downstream the Cherenkov detector.

Important steps in the development of the Super-FRS gas detectors was realized.

- The integration of new charge sensitive preamplifiers (CSA) with high dynamic range (up to  $5 \times 10^4$ ) and low gain (3 mV/fC) into the readout of the GEM-TPC detector allowed to investigate the performance of the detector in the  $^{238}\text{U}$ -ion measurement. A new board based on AWAGS - chip (Amplifier With Adaptive Gain Setting) designed at GSI with 256 channels was produced and tested at the FRS in collaboration with PANDA. The single-strip anodic-signals were digitalized using the FEBEX electronics. The FEBEX DAQ was combined with the FRS tracking detector readout for obtaining position resolution measurements at different GEM amplifications.
- This development is also considered as a candidate for the front-end readout of the planar GEM-Tracker stations of the PANDA experiment.
- A new fast and low noise 16-ch preamplifier card was developed by Mesytec as a prototype electronics for the Super-FRS MUSIC detector. The integration of the board on the detector, presently ongoing at DTL, will allow to measure in-beam dE for the PID system at the Super-FRS.
- The current-to-frequency converter IFC3 was tested to integrate intense beam currents measured by the ionization chamber and SEETRAM detectors with  $^{12}\text{C}$  at 60 AMeV and  $^{107}\text{Ag}$  at 300 AMeV. The results of these in-beam contributed to further improvements in the design of the intensity monitor Particle Detector Combination (PDC) of the Super-FRS. In addition, using the same GSI devices an irradiation test was performed with 62 MeV proton beams at LNS-INFN in order to study the variation of performance of FBK Silicon Photomultipliers.

A prototype detector setup of a GEM-Tracker for PANDA FAIR Phase-0 has been set up. Components of this device with technological key features have been tested successfully in-lab and in-beam at GSI.

A variety of compact MUSIC-type detectors have been built, set up and successfully operated during various experiments at R<sup>3</sup>B and FRS at GSI providing precise energy-loss measurements as input to the PID system. The design was especially optimized to reduce the noise- and electromagnetic interference contributions to the detectors signal in the harsh environments of the experiments. The detector systems are considered to replace standard beam-diagnostic equipment in the future.

In the framework of the development of the “next generation scanning system” for intensity controlled raster scanning in the medical cave, a GEM-based detector system has been operated successfully in various beam-times. It offers a ten times faster intrinsic response and thus position determination during an irradiation which is especially important considering the irradiation of moving targets a/o an accelerated dose application. The detector is equipped with commercially available ASICS providing 64-channel charge measurements with 200fC resolution on a time scale in the order of 10 $\mu$ s.

## 10. Research of the Department IT

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

In close collaboration with the experimental groups at the GSI/FAIR and external institutes (e.g. CERN and Dubna), the IT department is developing and maintaining ready-to-use tool sets that can handle the high-throughput data analysis and simulations for the different experiments [1-3] (e.g.: ALICE, CBM, PANDA and R<sup>3</sup>B).

In preparation for the LHC RUN3 (2021) a new package that should take care of the online farm control for ALICE and the FAIR experiments is being developed. The Online Device Control (ODC) package [4] is a controller for online computing farms. ODC uses the DDS [3] as process deployment system but also support the usage of the standard Slurm/PMIx tools [5,6] when available. The ODC was successfully used to control more than 30,000 process running on the test system of ALICE at CERN (more than 5000 cores). It was also tested on the new GSI Farm (Virgo). ODC will also be tested/used with the mini-CBM online cluster in the near future.

The Alice Analysis Facility prototype at the GSI already built last year has undergo further tests that confirmed a significant increase in scalability and performance by the utilization of the "XRootD Local Redirect plug-in" [7]. The integration and tests in analysis productions using the AliROOT framework are in progress [8].

Within the European Open Science Cloud (ESCAPE) project [9] activities, a first prototypical distributed storage infrastructure for FAIR, a data lake, is being developed and set up. Furthermore, the development of the SPACK [10] based build system is ongoing for the different packages. Preparation for making the GSI-IT software packages available to the wide scientific community through the planned ESCAPE repository are ongoing.

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## 11. 39<sup>th</sup> Summer Student Program at GSI

Organizers: Prof. Dr. Jörn Knoll, GSI; Dr. Yvonne Leifels, GSI; Dr. Haik Simon, GSI; Dr. Ralf Averbeck, GSI; Prof. Dr. Henner Büsching, HGS-HIRE; Dr. Gerhard Burau, HGS-HIRE  
Author: Prof. Dr. Jörn Knoll



Figure 45. Group photograph of the participants of the 39<sup>th</sup> summer student program.

For our 39<sup>th</sup> summer student program we were welcoming 37 students on the last-year Bachelor- or Master-study level (see Figure 45). The students came mostly from Europe, and a few from Asia. Ten of the more than 30 tutors mentoring our summer guests were former summer students.

During the eight weeks of the program each student was working on a small scientific or technical project supervised by a tutor. In addition a lecture series was held that provides a survey over the various research fields and applications at GSI/FAIR including a special Summer Colloquium presenting the research projects and space operations of the European Space Agency (ESA). The program was supplemented by introductory soft skill courses.

During the final week the summer students have organized a series of seminar talks, where each participant was reporting on her/his summer project. Furthermore the students were editing a report book that collected all the project reports mixed with student-life photos from the social and sport events, like the pedestrian rally, the barbecue party, the diverse weekend excursions or GSI's football cup, where this year the Summer Student team was winning the silver cup. Every summer student obtained a report book as a souvenir on the eight summer weeks shared with their summer fellows here at our research center.

The program was organized together with our Helmholtz Graduate School HGS-HIRE. Further details can found on our web-pages: <https://theory/gsi.de/stud-pro/> and <https://hgs-hire.de/summer-program>.



## 12. Technology transfer

Head of the department: Dr. Tobias Engert

Author: Dr. Tobias Engert, GSI, and Dr. Yvonne Leifels, GSI

Technology Transfer (TTR) is a staff unit with 4.6 FTE and reports directly to the Administrative Management. TTR supports GSI/FAIR scientists presenting their developments to industry and making connections to companies for high end technologies. In addition, the staff unit is responsible for the processing of services and contract research, innovation management, business development and technology marketing.

### Activities in 2019

An interdisciplinary patent committee, consisting of nine GSI members, evaluated (economically, technically) the GSI patent portfolio with respect to the individual terms of office as well as the newly submitted invention disclosures. This information was collected and worked out by TTR and the Patents Group in the Legal Department. During this review process, the portfolio was reduced from 540 national and international protective rights to 426 patents in 2019. The evaluation is ongoing and aim to create an economic patent portfolio in accordance with the requirements of the corporate strategy.

As part of a BMBF-funded initiative, Technology Transfer is developing a “Transfer Instrument for the Exploitation of Waste Technologies from Major Scientific Projects”. The project, which is funded with approximately 900,000 Euro, has started in December 2018 and will run for three years. The aim of the project is to improve the identification, securing, further development and transfer of innovations from large research infrastructure projects. In particular, the initiative aims to identify and exploit the innovation potential inherent in the development and construction of FAIR. For this purpose, so-called Technology Liaison Officers (TLOs) have been installed (1.6 FTE). In the long term, the aim is to increase the return flow from large-scale research projects to society.

### Marketing activities of TTR

The development and marketing of the emittance scanner “ROSE” (rotating scanner for 4-dimensional emittance measurements) is a successful transfer project in 2019. The detector system ROSE, allowing to perform 4D emittance measurements on heavy ion beams independent of their energy and time structure, has been build and successfully commissioned at GSI.

Precise information on and manipulation of the emittance of the ions in an accelerator are necessary tools to improve the beam quality. Until now, only the horizontal and vertical projections of the 4D phase space of heavy ions at energies  $> 100$  keV/u could be measured. This measurement lacked information on the coupling of these planes. With the patented rotatable emittance measuring system ROSE, the couplings of the planes can now be measured for the first time and thus accelerators can be adjusted much more efficiently.

An integrated software package will be developed for the detector system ROSE and the electronic control system “Robomat”, which combines planning, measurement, analysis, and adjustment of the 4D emittance measurement. This project is supported by the Hessian LOEWE initiative for three years with more than 360,000 Euros in the Funding Line 3: SME joint projects”; applicant is the company NTG, Neue Technologien GmbH in Gelnhäusen, which cooperates with GSI.

Outside the funding project, the prototype will be tested at GSI in routine operation, optimized together with NTG and finally offered by NTG on the market as a complete system. The prototype used routinely at GSI will also serve NTG as a demonstrator. Forecasts expect a worldwide market share of about 20% and the employment of dedicated personnel by NTG. In addition, the ROSE emittance measurement will enable the implementation of numerous new research projects in the field of FAIR accelerator physics.

### Marketing of the Green IT Cube and IT container

After two years of negotiations with the company NDC Data Centers GmbH (which acquired the company e3computing GmbH, with which GSI negotiated before), the innovative and energy-saving data center cooling technology applied in the GSI Green IT Cube was successfully marketed together with the Goethe University Frankfurt (GU) in November 2019. With this concept data centers can be operated with up to 50 % less primary energy input compared to conventional methods.

The Munich-based company NDC Data Centers GmbH was granted the rights to exploit the Green Technology in data center construction around the world; this was announced in February 2020 at a press conference attended by the Hessian Minister of Science Angela Dorn.

### Networking activities

In addition to the regional and national network activities (IHK Darmstadt, "Cyber Security Hub"- Digital City of Darmstadt, Merck, cooperation with ESA, EEN Hessen, NANORA as well as the TTGR of the HGF), Technology Transfer is also involved in the European TT network "HEPTECH"- High Energy Physics Technology Transfer Network. HEPTECH was founded in 2008 with the goal of a European High Energy Particle Physics strategy, and currently comprises 16 international member institutes such as CERN, ESS or ELI. In December 2018, Dr. Tobias Engert, Head of Technology Transfer of GSI, was elected Chairperson of HEPTECH.

In the last year, 21 companies, especially from Germany, Italy, Slovenia, France, Poland and Sweden, took part in the industry roadshow, which is regularly held on the campus. Apart from normal interest in products or processes, the opportunities for joint development work were explored. This resulted in 7 new R&D cooperation agreements and 37 new R&D contracts in the reporting year.

# 13. Research & developments of the FAIR Project and specialized departments

Head: Jörg Blaurock, GSI & FAIR

Authors: Emmanuel Rosi and Mandy Raponi et al., GSI



Figure 46. Overview of construction site area north and south.

## Executive Summary

In early 2019, the “FAIR Project and Cost Review Board” has been performed by the international review team led by Lynn Evans. The final review report was presented to the FAIR Council on the April 29<sup>th</sup> 2019. The review team has confirmed the scientific relevance of the entire FAIR experimental program and expressed its opinion that the breadth and reach of these programmes will re-main unsurpassed at the planned start of FAIR operation in 2025 and for many decades beyond. The review panel also recommended on one hand the FAIR Council to ensure the continuity of the FAIR civil construction through the appropriate financing and on the other hand a staggered commissioning sequence, if necessary, starting with Super-Fragment Separator (Super-FRS) and SIS18 in order to achieve the earliest start of science date as possible.

The above recommendations have been followed by the Council in December 2019 where the construction of an “Intermediate Objective” including the complete scope except the buildings for Collector Ring (CR), High-energy Storage Ring (HESR) and proton-Linac (p-Linac) and financed by Germany has been decided. The construction of the Modularized Startversion, which remains the goal of all Shareholders, will be further financed with the remaining contributions by all Shareholders.

In 2019, the major steps in the civil area have been the start of tender of major Technical Buildings Installation packages, according to FAIR Council decision, in July 2019 and the further steps in negotiating the civil work contract for the south area whose award is planned in April 2020.

On the construction site, the main focus has been put on the remaining excavation works for the SIS100 tunnel and the CBM building as well as the civil works for the SIS100 tunnel and the transfer building, which are both located in the northern construction area (see Figure 46).

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 have ramped up continuously in 2019. Significant progress and milestone achievements can be reported. Such as:

- delivery of the first of two injection septa for the High Energy Storage Ring, HESR, by the company Sigmaphi (Vannes, France) to Jülich,
- signature of the cooperation contract for the cold testing of more than 80 SIS100 quadrupole modules at the National Facility for Superconducting Systems, NAFASSY, at the university of Salerno (Italy, GSI In-kind),
- delivery of the first 8 series power amplifiers of the stochastic cooling system of the Collector Ring, CR, to GSI,
- successful final acceptance test of the main series (67 pcs.) of quadrupole power converter for the High Energy Beam Transport, HEBT, delivered by Electronics Cooperation of India Limited, ECIL,
- signature of the In-kind contract for the SIS100 Cryogenic Bypass Line with Wrocław University of Science and Technology, WUST (Poland),
- signature of the In-kind contract for the SIS100 Feedbox with WUST (Poland)
- signature of the GSI In-kind contract for the cryogenic plant at the end of October 2019.

### Experiments and FAIR Phase-0

The international FAIR experiment collaborations, APPA, CBM, NUSTAR, and PANDA, On the experiments' side, the international collaborations continue the construction of the detector components for the experimental setups for FAIR Day-1. The high scientific potential of the Day-1 configurations was confirmed in a comprehensive evaluation of the whole FAIR project beginning of 2019.

Some highlights achieved in the year 2019 include: CRYRING, a Swedish contribution, continues its commissioning with beams from its own sources. Construction of large systems of APPA HED@FAIR and SPARC commenced, following the conclusion of the Final Design Reviews. In the FAIR Phase-0 beam time, the CBM collaboration has successfully performed first experiments with the mini-CBM setup, which is composed of prototypes of all detector systems of CBM. First test experiments of the NUSTAR-R<sup>3</sup>B collaboration were performed with the fully operational GLAD magnet, a large German-French contribution to the experiments. For PANDA, the construction of all octants of the yoke of the large solenoid magnet was completed at the manufacturing company in Russia and the tender for the Barrel DIRC quartz bars was successfully concluded.

## 13.1 Research & developments of the division SIS100/SIS18 of the FAIR Project

Head: Dr. Peter Spiller

SIS100 Status Report



Figure 47. Second and third acceleration cavity in final assembly.

A large fraction of the series of SIS100 superconducting dipole magnets have been manufactured, shipped to GSI and successfully cold tested. The high quality of the magnet geometry and correspondingly the magnetic field could be maintained in all magnets produced so far.

After delivery of two FOS quadrupole units made at JINR, Dubna, the integration of the cold mass of the FOS quadrupole module has been completed at Bilfinger Noell, Würzburg. After installation of the cold mass in the cryostat vessel, the first module has been delivered to GSI. In parallel at GSI, the technical preparations for the cold testing of the FOS quadrupole modules have been completed. The cold testing of the FOS quadrupole module at GSI is used for training of the project team from INFN, Salerno. The contract for the series testing of the quadrupole modules in Salerno, Italy has been signed by the INFN directorate and the GSI management in July 2019. Based on this contract, the preparation of the NAFASY test facility at Salerno for testing the SIS100 quadrupole modules has been launched.

In order to maintain the schedule, advanced procurements of parts of the series of quadrupole modules have been released. A major issue for the GSI design office is the completion of the manufacturing drawings for the upcoming modules in time and to implement design modifications proposed in the manufacturing process.

At JINR, the first yokes for the series production of the quadrupole units have been arrived from the manufacturer in Minsk. However, because of large geometrical deviations from the specified tolerances, several yokes had to be rejected by JINR and sent back for revision.

As one of the last items with long production times, the procurement process for the main dipole- and quadrupole power converter has been launched by GSI. However, the procurement process had to be terminated and options for cost reductions have been investigated.

The manufacturing of SIS100 RF systems is progressing. At research instruments (RI), two more acceleration cavities have been completed (Figure 47). For the power tests, the next power converter of the series which is presently in assembly at AMPEGON, Switzerland, shall be shipped to RI.

In the course of 2019, a solution has been developed, which saves the continuation of the contracted contributions of the company AMPEGON which entered into financial difficulties. The pulse power part of AMPEGON in Dortmund has been taken over by RI and the power converter part by OCEM, Italy. Thus, the completion of the power converter manufacturing for the SIS100 acceleration system is assured and can be continued. The delivery of the SIS100 ionisation profile monitor (IPM) magnet system and the bakeable vacuum chamber by Co. Pfeiffer marks an important milestone in a complex project that involves several technical departments. The magnet system has been installed, connected to power supplies and acceptance tested.

For the SIS100 beam instrumentation system, the series production of the cryogenic BPMs has been started at the former company FRIATEC. The first batch of cryogenic BPMs have been delivered and has passed several thermal cycles without issues. In order to generate safety in terms of the availability of BPMs for the series integration of quadrupole modules, a second, parallel production line has been set up by awarding another batch of BPMs to Kyocera for production in Japan. This contract has been initiated, since a former prototype BPM manufactured by Kyocera, Japan has passed thermal shock tests without any damage.

Major progress has been achieved in respect to the Polish In-kind contribution to the SIS100 local cryogenics system. All contractual issues related to the bypass lines and current lead boxes could be solved. Furthermore, the In-kind contract for the feed-boxes and the feed-in lines has been signed by all parties in August 2019. Thus, contracting the full SIS100 local cryogenics system is completed. The manufacturing of the bypass lines has been awarded by the Polish provider to the company Kriosystems. Kick-off meetings have been organized for the production of the bypass lines and for the design of the feed-boxes.

## The SIS100 laser cooling facility

**Authors:** S. Klammes<sup>1,2</sup>, M. Bussmann<sup>3</sup>, V. Hannen<sup>4</sup>, D. Kiefer<sup>2</sup>, T. Kühl<sup>1,5</sup>, X. Ma<sup>6</sup>, P. Spiller<sup>1</sup>, U. Schramm<sup>3,7</sup>, M. Siebold<sup>3</sup>, T. Stöhlker<sup>1,5,8</sup>, T. Walther<sup>2</sup>, W. Wen<sup>6</sup>, and D. Winters<sup>1</sup>

1 GSI Helmholtzzentrum, Darmstadt, Germany; 2 Technical University Darmstadt, Germany; 3 Helmholtz-Zentrum Dresden-Rossendorf, Germany; 4 Münster University, Germany; 5 Helmholtz Institute Jena, Germany; 6 Institute of Modern Physics-CAS, Lanzhou, China; 7 Technical University Dresden, Germany; 8 Jena University, Germany

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

Laser cooling is well established for atom and ion traps, where the velocities are very low, but can also be applied to relativistic velocities, where the huge Doppler-shifts are being exploited to cool extreme ions using ‘normal’ lasers. Calculations have shown that relative ion beam momentum spreads of  $\Delta p/p < 10^{-7}$  (depending on the ion beam intensity) and cooling times of only a few seconds are possible [2]. Correspondingly, also intense ultra-short ion bunches can be created, even shorter than those obtained using the bunch compression method (50 ns). This will offer unique possibilities for extracted beams from the SIS100, especially for the generation of high energy-density in matter (e.g. dense plasmas).

The laser systems for this work are being developed and built by the TU Darmstadt (cw laser & pulsed ps-ns laser) and the TU Dresden/HZDR (ps pulsed laser), supported by the BMBF. The pulsed laser systems have variable repetition rates (up to 1-10 MHz). This offers the unique possibility to synchronize the laser pulses with the ion bunches in the SIS100, and could further increase the laser cooling efficiency. All laser systems use frequency doubling stages to convert the initially IR laser (1028 nm) light, via visible light (514 nm), to the final UV light (257 nm). These laser systems have up to a few 10 W of average power. The laser systems will finally be transported to and installed in the SIS100 maintenance tunnel (where the laser lab will be).

The detector system, which will detect the fluorescence from the laser excited ions during laser cooling, will be built by the University of Münster (BMBF support). A similar system has already been successfully tested at the ESR in 2016 using stored  $^{12}\text{C}^{3+}$  ions. At the SIS100, the Doppler shifts are much larger, uniquely enabling laser cooling studies with more intense and much heavier ion beams. However, the XUV fluorescence will shift to much smaller wavelengths, requiring partially different technology, which is currently being developed in Münster [3].

The SIS100 vacuum chamber (built by Kurt. J. Lesker) was shipped and tested at GSI [4]. The chamber is made out of the highest quality stainless steel (electro-polished), and comes with a frame, alignment bridges, bellows (Witzenmann), and heater jackets (Iso-heat). The chamber has now passed the vacuum Site Acceptance Test (SAT) and awaits installation at the SIS100.

List of components purchased in 2019:

- DFB laser (Dynamic Feedback) + controller (Toptica)
- chiller for laser system, ,max. 1200 W (FRYKA)
- Laser Spectrum Analyzer (Toptica /HighFinesse)
- 2 optical shutter systems (MRC and Thorlabs)
- 2" optical mounts (Thorlabs & Newport)
- UV mirror set 2" and 3" (CVI/Melles Griot)
- DN160CF pressurized vacuum valve (VAT)
- DN200CF ion pump (Agilent Vaclon Plus 500)

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## SIS18 developments and upgrade for FAIR

Authors: P. Spiller, S. Aumüller, L. Bozyk, T. Giacomini, P. Hülsmann, A. Krämer, C. Mühle, D. Ondreka, V. Plyusnin, N. Pyka, P. Rottländer, M. Schwickert, R. Singh, J. Stadlmann, H. Welker

### Developments for FAIR Phase-0



Figure 48. New SIS18 micro spill cavity for FAIR Phase-0.

A new beam chopper system used to shape the UNILAC beam for injection into SIS18, delivered by the company AURION, has been installed and successfully commissioned. The new chopper provides much faster rise time of the pulse and consequently less uncontrolled beam loss.

A key issue for the operation in FAIR Phase-0, is the improvement of slow extraction performance, both in terms of extraction efficiency and micro spill structure. Several machine experiments indicate, that the deflection angle of the electrostatic septum is insufficient for operation at maximum beam energy (maximum electric rigidity). Since the origin of this missing deflection angle is not fully understood, various investigations and simulations have been conducted to improve the understanding of the underlying processes. In parallel, the design for a new, prolonged electrostatic septum has been developed and completed. The design of the longer septum is based on the design of the SIS100 septum. Improving the extraction efficiency at highest beam energy and intensity is also essential for radioprotection and activation reasons which both define limits for the maximum beam intensity.

With the goal of smoothing the micro spill structure, several approaches have been launched. On one side a tune wobbler system has been set-up and successfully commissioned with beam [1] and on the other side a new high frequency cavity has been prepared for installation in the shut-down 2020. The new cavity is a refurbished UNILAC single resonator which generates a harmonic bucket at about 100 MHz (Figure 48). The installation of the new spill smoothing cavity was originally planned for 2019. However, due to a fail function of an Rf sealing the installation had to be postponed.

## Upgrade for the FAIR Booster Operation

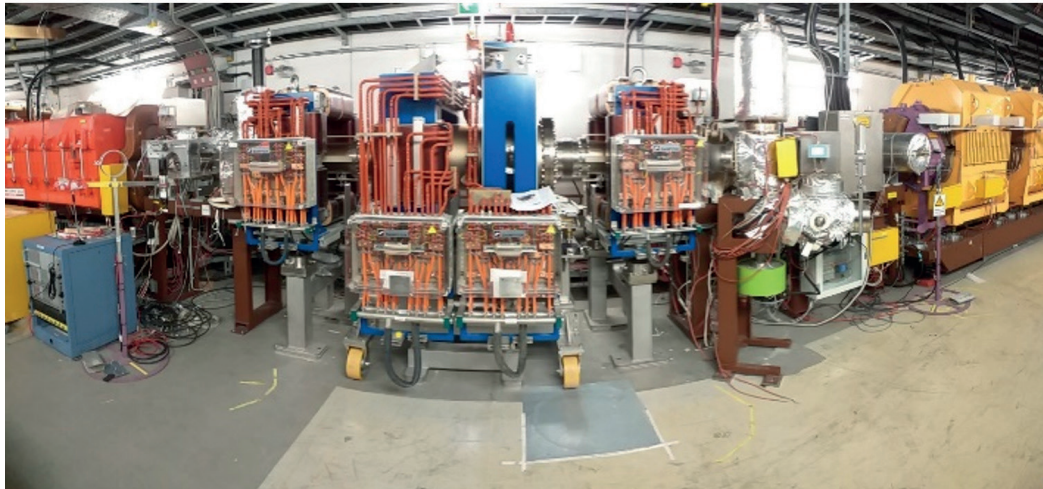


Figure 49. The new IPM magnet system installed in SIS18.

The two last items of the originally defined SIS18 upgrade [2] program still to be completed, are the IPM monitor for turn-by-turn beam profile measurements and the new bipolar dipole magnet GS1MU1. The latter deflects the beam from the GSI HEBST system towards FAIR. The IPM magnet system, the power converter and main vacuum chamber have been installed in 2019 (Figure 49). In order to complete the system, the magnets still have to be connected to the power cables and the water cooling system. Furthermore, the main parts of the IPM monitor, the HV caves with the detector systems are presently prepared for installation.



Figure 50. SIS18 cryogenic test chambers at ILK, Dresden.

During the acceptance tests of the new bipolar dipole magnet, several non-conformities were identified which needed to be corrected by the manufacturer. After mitigation and repeated testing, the dipole chamber has been integrated into the magnet and cooling final tests and tests with fast bipolar ramping were launched. Another major progress for improving the SIS18 operational performance has been achieved by the commissioning of the new FAIR real-time closed orbit feedback system [3]. The system has been fully implemented in vertical plane and its functionality has been successfully demonstrated in the frame of machine experiments.

In order to explore further options for enhanced pumping power and stabilization of the dynamic vacuum at U28+-operation, a cryogenic test chamber has been designed and manufactured (Figure 50). The cryogenic test chamber is presently undergoing the acceptance phase at the company ILK, Dresden. With this chamber the possibility to replace the room temperature vacuum chambers in SIS18 by chambers with cryogenic inserts will be studied.

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## 13.2 Research & developments of the division Super Fragment Separator of the FAIR Project

Head: Dr. Haik Simon



Figure 51. FoS SC short multiplet on its testing bench (CERN, Geneva, Switzerland).

The subproject Super-FRS consists of three main groups comprising technological challenges: a super-conducting-magnet system allowing for large apertures, a target area suitable to withstand the high primary beam intensities provided by the SIS100 synchrotron, and the diagnostic systems with high rate capability. In addition, the use of advanced cryogenic and vacuum technology is required all along the machine. The whole system serves the class of experiments, which requires clean and intense beams of unstable, short-lived nuclei that exhibit special properties very far from the valley of  $\beta$ -stability. The Super-FRS will be one of the few most powerful sources for exotic isotopes world-wide.

The components belonging to the first group are the superconducting magnets including their power converters and the quench detection and protection system. The large-aperture superconducting magnets consist of 24 dipoles and 175 multipoles. Three out of the 24 dipoles have a special design to allow a branching of the separator towards the three different experimental areas. The multipoles are arranged in 30 groups, which are called “multiplets” and represent the magnetic lenses of an ion optical system. In each multiplet several magnets are embedded in a unique vessel, which is refrigerated as one piece with a weight of several tens of tons. These superconducting magnets are already in the production phase, with the exception of the branching dipoles, whose Research and Development (R&D) is still ongoing. The demanding local cryogenic system, aiming at controlling a phase mixture of liquid helium and distributing it at a few Kelvin absolute temperature over several 100m distance towards the magnets, is finalising its R&D phase. A set of dedicated power converters including the quench detection system, in the same power-converter cabinet, are currently in their final R&D phase and the production of a prototype power converter consisting of a double PC unit integrated into a common cabinet is started.

The target area faces a particular technological challenge due to the special constraints imposed by the highly radioactive environment. All components will be hosted in a narrow tunnel, built of iron and concrete, and acting as radiation shield. There will be only a few centimetres clearance between the components and the sidewalls to limit air activation in this tunnel. The iron shielding encloses (i) the target chamber with a graphite rotating target, (ii) 3 radiation-hard normal conducting dipoles, 3 quadrupoles and 2 sextupoles, and (iii) 3 chambers hosting a beam catcher system with removable plugs. All components including the three 90-ton dipoles are operated and aligned to sub-millimetre precision via sophisticated remote controls. Most of the components in

the target area are closing the R&D phase, some of them are also in their final design phase or entering production.

All along the Super-FRS, vanguard detecting-system and radiation resistant electronics with very high rate capabilities of several Megahertz are being used. The detector and degrader systems are hosted in special vacuum chambers (called “diagnostic chambers”), located in each focal plane. The diagnostic chambers are starting the production phase; almost all detectors have finished the R&D phase, some of them are already in design phase prior to production. In this context, 2019 has witnessed important steps of progress.

At the newly built magnet testing station at CERN, the First-of-Series superconducting (sc) short multiplet was set on its testing bench and the Site Acceptance Test-phase started by cooling down the magnets assembly. The cooling process proceeded very satisfactorily within the expected cool-down rate. The full magnetic measurement campaign on the long quadrupole was successfully completed. The results showed good agreement with the simulations. The company ASG, Genova, Italy, produces these sc multiplets. The Final Design Report of the standard sc dipoles was completed successfully. The company Elytt (Bilbao, Spain) is producing the 21 standard sc dipoles. A contract for the production of the vacuum chambers of the sc standard dipoles has been signed with the Budker Institute for Nuclear Physics (BINP), Novosibirsk, Russia.

The detailed technical design of the sc branched dipoles, including their vacuum chambers, was concluded and the relative documentation was approved. The technical study was performed by our collaborators at CEA Saclay, France, who are also responsible for the follow-up the components. These three sc branched dipoles required a special design since they must be able to guide the beam into one of the three Super-FRS branches. Their vacuum chambers have a particular Y-shape. BINP is considering to take-over the production of these three vacuum chambers.



Figure 52. Design of shielding wall in the target areas.

The contract with BINP for the production of two normal conducting radiation-hard dipoles was signed on March 15<sup>th</sup> 2020. The special radiation hard cables, to be assembled into the Normal Conducting (NC) dipoles, were procured via FAIR and are stored at the GSI campus; they will subsequently be shipped to BINP. Moreover, BINP agreed to produce the NC dipoles' vacuum chambers too, including the very challenging design of a titanium shield being inserted into the chamber, and acting as a primary beam disperser. The R&D of this radiation shield is successfully ongoing. BINP also started a R&D activity to study the challenges within the demanding construction of the normal conducting radiation resistant multipoles in the target area.

In the frame of two cooperation agreements, R&D of the local cryogenics is ongoing with our two partner institutes: the Wroclaw University of Science and Technology (WUST), Poland, and Budker Institute for Nuclear Physics (BINP), Russia. The first is devoted mostly to the study of pipes, jumpers and feed-boxes, the latter mainly to the technological design concept of the branch box, which is the starting point for distributing helium to the Super-FRS experimental branches. A workshop

took place at GSI on 19<sup>th</sup> and 20<sup>th</sup> August; another meeting took place in Novosibirsk, on November 25<sup>th</sup> 2019, and fostered the way for the international collaboration.

The quench detection system for the Super-FRS sc magnets was developed; the Quench Detection units will eventually be integrated into the power converter cabinets, which will be provided by our in-kind partner in India. Intensive activity on the development of the power converter prototypes also occurred.

Concerning the target area, one of the most important achievements was the finalisation of the design of the lateral iron shielding blocks, and the subsequent start of tender with the publication of the call for bids. The iron shielding is necessary in order to reduce the radiation dose rate outside the target area to less than 0.5  $\mu\text{Sv/h}$  during Super-FRS operation. The lateral shielding consist of two rows of big iron blocks on each side having a thickness of 1.6m each. In addition, a shielding roof, made of at least 0.80m of steel plates with an extra of 0.2m concrete cover, is required. The specifications for the iron roof are in progress.

A great advance is also the finalisation of the in-kind contract with Finland and with the Swedish Shareholder for the production of the shielding flask. The shielding flask is used to transport the activated parts from beamline to a devoted shielded room complex (the "hot cell"). This flask must fit for many parts of beamline equipment. It is operated in the target building and moved by the 80ton-load hall crane.

Also the specifications for the beam catcher in target area were finalised. These components are required to catch safely the unreacted primary beam after the target as well as a large share of the unwanted fragments. Their design was challenging because – contrary to normal beam dumps – the beam catcher must be integrated directly into the separator without matter in between.

The target chambers is also an extremely complicated design. The design is carried out by the KVI-Center for Advanced Radiation Technology (KVI-CART), at the University of Groningen, Netherlands. The Pygmy Dipole Resonance (PDR) on target chamber has been approved.

On March 15<sup>th</sup> 2019, the contract for the production of 21 diagnostic vacuum chambers was signed with BINP (Russia). The chambers will be placed at the Super-FRS focal planes; they will host the beam instrumentation. The conceptual design report (CDR) for the First-of-Series chambers was finalised.

In April 2019 the kick-off meeting for the SEM GRID Detectors (Beam Profiler) was held at GSI, the production schedule (CD0) was accepted in May 2019. The purchase of material for the manufacturing of parts of the Particle Detector Combination (PDC) has started at GSI. Dedicated electronics developments to be used for the MUSIC DE detectors as Finnish In-kind have been procured under the supervision of GSI within the collaboration. The conceptual design report of the Music detectors was approved. The specifications of the Data Acquisition system for Super-FRS experiments was finalised too. The IK contract for ladders for position detectors was signed by the Finnish IK-partner and by the Swedish shareholder.

As a consequence of the Lean Construction Management (LCM) workshops for the building in the south area, several activities for the planning of installation, technical infrastructure and integration aspects have progressed. A series of installation workshops for the detailed implementation of Lean Construction Management (LCM) results started. A first workshop was held in June 2019. Successive workshops for the definition of the pre-assembly working-steps of superconducting magnets, diagnostic chambers, and vacuum elements were also done.

In summary the Super-FRS project is currently in its contracting and prototyping phase. Several challenging design steps have been undertaken and the project is subsequently advancing into construction phase.

## 13.3 Research & developments for the proton linac of the FAIR Project

Head: Dr. Klaus Knie

p-Linac



Figure 53. Full length RFQ electrode structure with rings (top). Assembly of the ladder structure inside the RFQ tank (bottom).

The commissioning of the proton source for the p-Linac was successfully performed at CEA/Saclay, France. The dismantling of the source and the transport to GSI has started.

The production of all parts of the ladder radio frequency quadrupole RFQ prototype was finished (see Figure 53). The RFQ was assembled for tuning tests. The mechanical overwork of the ladder structure to optimize the field flatness was successfully completed.

Tests of the copper plating of dummies and welding procedures for the crossbar H structures are progressing (Figure 54). The couple cells have been redesigned to facilitate the assemble of the triplet lenses.

The in-house production of the first-of-series modulator is in progress with the work focusing on the pulse transformers. 10 Low Level Radio Frequency (LLRF) controllers and 10 racks were delivered as an In-kind from I-tech, Slovenia.

For the p-Linac beam diagnostics system several important steps could be taken in 2019. The 15 Beam Position Monitors (BPM) (see Figure 54), were delivered as well as the data acquisition (DAQ) and electronics of the BPMs system, which is also a Slovenian in-kind contribution produced by

I-Tech. The specification for the BPM FESA class was submitted to COSYLAB. FESA is the abbreviation for Front-End Software Architecture, which is an environment to design, develop, test and deploy real time control software for accelerators. FESA was developed at CERN.

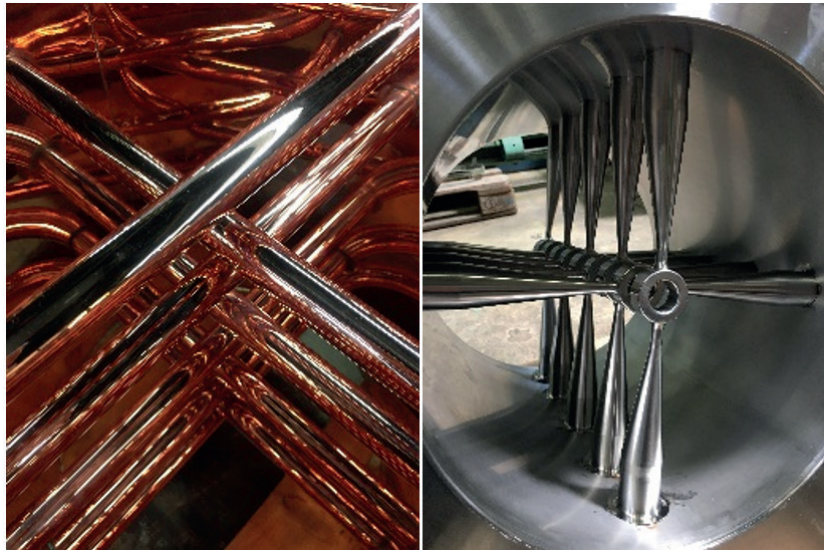


Figure 54. First copper plated dummy structure (left). Welding test (right) waiting for copper plating at GSI.

The remaining seven BERGOZ current transformers were delivered in summer 2019. At the same time production of the Bunch Shape Monitor started at INR Moscow.

An important result could be achieved during a beamtime at X2, showing that the POLAND+CSA (Charge Sensitive Amplifier) Scanning Electron Microscopy (SEM) grid electronics can be used for short pulses at the p-Linac. This avoids costs and effort for transimpedance amplifiers (for each wire) in the tunnel. A SEM grid with 0.5 mm wire distance was specified.

The layout of diagnostic boxes in the radiofrequency quadrupole (RFQ) rebuncher section, in the Medium Energy Beam Transport (MEBT) diagnostics section and in the dipole/beam dump section was fixed. A scheme for loss monitoring and pulse length reduction using alternating current transformers (ACCTs) and beam choppers was developed. In parallel to the mentioned activities the work and discussion on the diagnostics testbench was ongoing during the year.



Figure 55. p-Linac Beam Position Monitors. Inter-Tank types (small), Beamline types (large).

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## p-bar Target

For collecting and focusing of the highly divergent antiprotons emerging from the target a so-called “magnetic horn” has been designed. The detailed specifications of the whole magnetic horn system are completed and the tendering has been started.

Specifications for all magnets and power supplies are close to completed. Although most magnet will be very similar or even identical to those used in the Collector Ring, directly after the target special radiation resistant magnets have to be used.

Whereas all standard, i.e. non radiation resistant magnets will be produced by BINP, it is presently under investigation, whether BINP has the capacities to design and produce the radiation resistant magnet types in time and a tender needs to be started. However, at least for the most critical magnet, the large dipole after target, it is possible to use a Collector Ring (CR)-type yoke which can be produced by BINP. A coil with radiation resistant isolation will be procured independently.

In order to meet the requirements of the Collector Ring, the ion optics of the p-bar separator is presently re-investigated together with BINP. Simulations with the existing ion optical layout result in transmissions close to 100 %, but with high beam losses in the CR during the first turns. These simulations will be continued in more detail to investigate the possibility of reducing the sextupoles in the p-bar separator beamline and to improve the beam’s matching to the acceptance of the Collector Ring.

Detailed specifications for the shielding flask of the p-bar target are finished and the tendering process has been started together with the Super-FRS group. This allows to exploit synergies for the two FAIR shielding flasks at the p-bar target and Super-FRS target. The work on detailing of the remote-controlled exchange system for highly activated components (target, magnetic horn) is progressing.

## 13.4 Research & developments for the Collector Ring of the FAIR Project

Head: Dr. Ivan Koop, Dr. Oleksiy Dolinsky

The realisation of the Collector Ring (CR) project has progressed in R&D, design, prototyping, production and testing of the major system components. The last two In-kind contracts on the construction of the stochastic cooling system by GSI (Germany) and two beam diagnostics devices (the broadband Schottky Pick-Up and the exciter for beam transfer function measurements) by ITEP (Russia) have been signed which means the Collector Ring is fully contracted. Technical design activities in the frame of the Russian In-kind contribution by BINP (Novosibirsk) have progressed with the successful completeness of conceptual and final design reports for different magnetic and beam diagnostic components. The production of the series radio frequency debuncher systems has been finished and the site acceptance testing is ongoing at GSI. Major steps have been made in the R&D, prototyping, procurement and testing of the stochastic cooling components. This report gives an overview of the main recent technical progress and developments.



Figure 56. First completed upper plate of the dipole yoke (left) and first set of coils (right) at BINP.

One of the important achievements is the start of the dipole magnet production at BINP. The Collector Ring dipoles will be of H-type and will have a deflection angle of  $15^\circ$  with maximum field of 1.6 T. The usable magnet gap is 140 mm while the horizontal usable aperture is 380 mm. The required relative integrated field quality must be in the range of  $\pm 1 \times 10^{-4}$  as given by the ion-optical calculations. In order to meet the requirement to the design ramping rate of 1 T/s, the magnet yoke is made of the laminated steel with the thickness of 1 mm. It consists of an upper and lower plate, side spacers and a pole assembly. The first completed upper plate of the yoke is shown in Figure 56. The field quality can be adjusted by placing of special plates at the pole shims. In addition, the poles will have dedicated holes in which magnetic elements can be inserted for a fine-tuning of the field homogeneity.

The coils have 88 turns with the maximum current of 1420 A. The maximum DC power loss of the magnet is 126 kW calculated for the ramping rate of 0.054 T/s as required for the polarity change within 60 s. The set of the first two completed coils is shown in Figure 56. The total weight of the magnet is 59.8 t including the yoke, coils, support and vacuum chamber. The magnets will be delivered to FAIR in nine pieces and will have to be preassembled at GSI for site acceptance tests. The delivery of the first of series dipole is expected in end of 2020.

The manufacturing of the Collector Ring vacuum chambers is progressing with the prototyping of the dipole and wide quadrupole/sextupole chambers at BINP. The dipole chambers will have a rectangular profile with the inner aperture of  $406 \times 148 \text{ mm}^2$  and the corners rounded at the radius of 40 mm. The wall thickness is 8 mm. The chamber is made of four parts welded together by the tungsten inert gas (TIG) welding as shown in Figure 57 (left). The wide quadrupole and sextupole magnets in the CR arcs will have common hexagonal vacuum chambers with the inner aperture of

428×268 mm<sup>2</sup> and the wall thickness of 6 mm. Each of the hexagonal chambers will have two ports for mounting of the vacuum pumps. Figure 57 (right) shows the manufactured prototype chamber at the BINP workshop. The wide quadrupole and sextupole chambers will have inner welded holders for the fixation of the special frames with microwave damping ceramic tubes for the stochastic cooling system. After testing at BINP, the prototype chamber will be delivered to GSI to verify the mechanical integration concept of the damping modules.

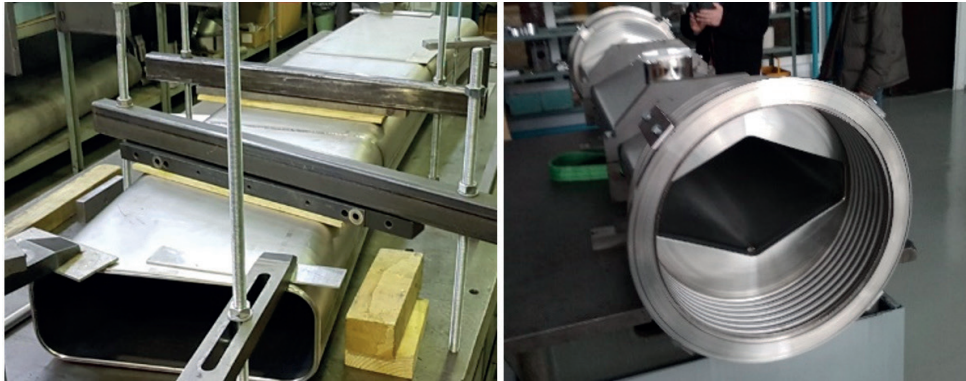


Figure 57. Dipole chamber in the manufacturing process (left) and the completed prototype quadrupole/sextupole chamber (right) at BINP.

The production of the radiofrequency (RF) system has been completed with the successful factory acceptance tests of the 4<sup>th</sup> and 5<sup>th</sup> series Power Supply Units (PSU) at OCEM (Italy). Five identical RF stations operating in the frequency range of 1.1 – 1.5 MHz will be installed in the CR for bunch rotation, de-bunching and re-bunching of antiproton and heavy-ion beams. The maximum gap voltage of one RF cavity is 40 kV in the pulsed mode and 2 kV in the continuous mode. After the successful commissioning of the 1<sup>st</sup> series system in 2016-2018, the 2<sup>nd</sup> system has been integrated and prepared for site acceptance testing at the GSI testing hall (Figure 58). The major technical challenge is related to the long-term operational reliability of the RF system. During the commissioning of the PSU units, unexpected sporadic shutdowns have occurred due to electromagnetic interference (EMI) disturbances originating from the pulsed step modulation (PSM) operation. A dedicated EMI study will be made by the provider to understand a reason of the shutdowns and find a technical solution. A corresponding contract covering the EMI study as well as a long-term support by OCEM has been agreed and signed.



Figure 58. The 2<sup>nd</sup> of series RF debuncher system during the commissioning at the GSI testing hall.

The prototype slot-line plunging pick-up of the CR stochastic cooling system has been tested at GSI to check the mechanical and cryogenic/vacuum design concept. Totally 128 electrodes will be installed in each of the two slot-line pick-up tanks to measure the beam signal. The electrode modules will operate at cryogenic temperatures in order to increase the signal to noise ratio, which is particularly critical for the Filter cooling of antiprotons. Furthermore, the electrodes will be synchronously moved by the linear motor drives from ±80 to ±10 mm towards the beam axis following the shrinking beam during the cooling. Figure 59 shows the assembled prototype pick-up prepared for the cryotests at the GSI test bench.



Figure 59. Assembled prototype slot-line pick-up prepared for cryogenic testing at the GSI test bench.

The measured temperature distribution of the electrode module body after the cooling down is close to the specified requirements. The mechanical concept of the pick-up assembly has been checked and measures for further improvement have been defined. The specification preparation and procurement of the vacuum tank will start after the required refinements of the mechanical design.

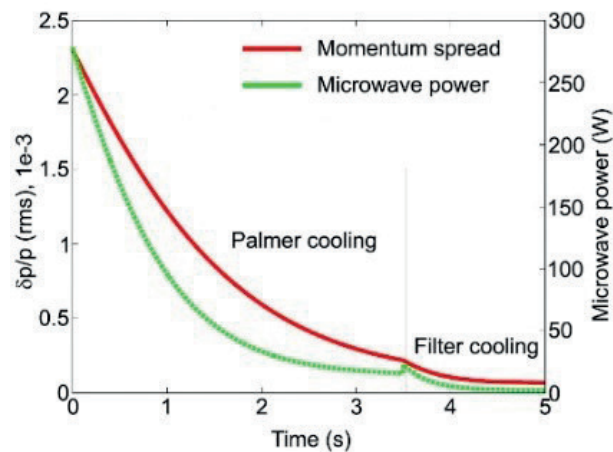


Figure 60. Momentum cooling simulations for the  $^{135}\text{Sn}^{50+}$  beam.

For operation with radioactive ion beams (RIB), a dedicated Palmer pick-up based on Falin-type travelling wave structure will be installed in the Collector Ring. The Filter method cannot be used for cooling of the hottest RIBs due to the large unwanted mixing between slot-line pick-ups and kickers. The momentum acceptance of the Filter method is  $\pm 1.4 \times 10^{-3}$  while the momentum spread of RIBs after bunch rotation and de-bunching is  $\pm 4 \times 10^{-3}$ . The Palmer method has the momentum acceptance of  $\pm 7 \times 10^{-3}$  and can be used for pre-cooling of RIBs. As soon as the momentum spread becomes less than the acceptance of the Filter method, the system can be switched to the Filter cooling which provides a larger cooling force and can efficiently cool the beam to the required qualities. As an example of the recent calculations, the Palmer method can pre-cool  $^{135}\text{Sn}^{50+}$  beam with the intensity of 108 ions during 3.5 s. With the following hand-over to the Filter method, the beam can be finally cooled to the momentum spread of  $7 \times 10^{-5}$  (rms) after 5 s of cooling as shown in Figure 60.

The inner structure and the vacuum tank of the Palmer pick-up have been manufactured and successfully tested at GSI (Figure 61). In 2020, the pick-up will be delivered to the Forschungszentrum Jülich (FZJ) for assembling and testing with beam at the COSY synchrotron.

The required engineering microwave power of 8 kW for simultaneous 3D stochastic cooling in the 1-2 GHz band will be provided by 32 water-cooled power amplifiers (250 W each) installed at the kickers. The commissioning of the preseries power amplifier was finished in 2017. Because of the limited reliability in the long-term operation, the RF combiner board has been redesigned by the provider. The series production has been released in 2018 after the successful site acceptance tests of the improved first of series device. The first batch (8 pieces) of the series power amplifiers have been delivered to FAIR after the successful tests at Vectawave (UK). The site acceptance testing is ongoing at GSI.



Figure 61. The Palmer pick-up vacuum tank at the GSI testing hall at the intensity of 108 ions/cycle.

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

Head: Dr. Dieter Prasuhn

The components with the longest delivery time for the High Energy Storage Ring (HESR), dipoles and quadrupoles were delivered completely to Jülich and technically approved. 42 of the 46 dipole magnets were preassembled in Jülich with vacuum chambers and delivered to Darmstadt for interim storage.

All power converters for the quadrupoles were delivered to Jülich. The delivery of corrector and sextupole magnets as well as the corresponding converters as In-Kind contribution from Romania are delivered to Jülich according to the schedule.

All other essential components are in production or series production and most of them will afterwards be delivered to Jülich. After pre-assembly, these components will also be fully transported to Darmstadt. The first installation window for the HESR tunnel is scheduled by FAIR Site & Building (FSB) for a few months in the first half of 2022. The legal release of the HESR building for usage is presently scheduled by FAIR Site & Building (FSB) for Q2/ 2023. At that time the installation of HESR can be completed and commissioning can start.

Series production of Beam Position Monitors, sectional valves, and ion clearing chambers is ongoing. Once these items are available the assembly of the quadrupole magnet girders for the arc sections will be started.

## 13.6 Research & developments of the division Commons of the FAIR Project

Head: Stefan Menke

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

- 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 (HEB)

#### Magnets

The series production of batch1 with in total 51 dipole magnets is running in full scale at Efremov Institute of Electrophysical Apparatus in St. Petersburg, Russia (NIIIEFA): In 2019 13 dipoles and three spare coils were delivered. By the end of 2019 eight of these magnets were equipped with vacuum chambers and transported to the temporary storage in Weiterstadt. At the same time  $\frac{3}{4}$  of the dipoles of the full contract were delivered.

Production of the magnets of batch2 and 3 (22 dipole, 166 quadrupole, 92 steering magnets) is carried out at the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia: The series of four dip15\_0 dipole magnets has been completed and delivered in 2019. 21 series magnets of Quadrupole 2 arrived at FAIR. In addition, two pairs of S18 steering magnets and two pairs of S100 steering magnets were shipped. Overall in 2019, 11,4% of the magnets of the complete contract were delivered. 15 more magnets underwent factory acceptance tests (FAT) in the last quarter of 2019. After repairing of minor issues and completion of documentation these magnets can be delivered in 2020, too.

#### 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. Another two power converters for dipole and six power converters for quadrupole magnets are planned to be contracted in the middle of 2020 with the same partners.

In 2019 the first series production of 67 power converters for quadrupole magnets HB.Q2 could be successfully finalised including delivery to FAIR storage hall. Another six HB.Q2 power converters are in production at ECIL, the shipment is planned for the beginning of 2020.

A first of series (FOS power converter for steering magnets HB.C1 was tested in April 2019. The series production and factory acceptance testing of 48 units have started. The delivery is planned for the beginning of 2020.

A FoS power converter for quadrupole magnets HB.Q11 was tested in October 2019. In the meantime procurement of components and the preparation for the series production of 36 power converters HB.Q11 has started, the delivery is expected in the end of 2020.

For 51 power converters for dipole magnets and 9 power converters for quadrupole magnets a European call for tender was initiated. The contracting of these power converters is planned for mid of 2020.

## Beam Instrumentation

The main focus of beam instrumentation department remains on the preparation of FAIR Day-0 diagnostic components required right from the start of beamline commissioning.

### *Transformers:*

Vacuum chambers with ceramic gap are delivered and tested. A full mechanical prototype is under construction. Currently, a specialised manufacturer is being evaluated for the deposition of a thin conductive layer of well-known and uniform surface resistance on the inside of the ceramics.

Two high-sensitivity fast current transformers (FCT) for the beam transfer between CR and HESR have been delivered by the company Bergoz in December 2019. This completes the available High Energy Beam Transport (HEBT) units for primary beams. An order for RT ferrite ring cores of standard size (CF 150 beam lines) has been awarded to National Magnetics. The delivery is expected in June 2020.

The cryogenic current comparator project saw the completion and delivery of the cryo-compressor to GSI at the end of 2019. The factory acceptance test (FAT) was performed and the system is being prepared for installation into the experimental storage ring CRYRING.

### *Beam position monitors:*

The inner ceramics with metallized electrodes for 40 ceramic BPMs are ordered. The ceramics are identical to the ones for SIS100. The first of series (FoS) unit was tested at GSI in December 2019 and delivery of the series will take place in June 2020.

### *Beam loss monitors:*

A first batch of 16 detectors was assembled and installed in the transfer lines of the GSI HEBT as part of an upgrade programme. The new detectors were commissioned and tested during regular machine operation. A few minor adjustments to the mechanical design resulting from this project are now introduced in the final mechanical model.

Procurement of mechanical parts and material for BPMs, scintillating screens, SEM detectors and beam loss monitors as well as related readout hardware is ongoing and will continue throughout the year.

### *Ionisation Profile Monitor:*

A collaboration between GSI and Forschungszentrum Jülich on the development on a common IPM design suited for HESR and HEBT alike started in 2019. The design of the complex inner field cage mechanics with multi-channel plate and scintillating screen was already completed in 2019. Ongoing work focussed on the mechanical aspects of the optical readout system.

### *In-kind Slovenia:*

The cooperation with all Slovenian in-kind providers within the Technodrom consortium continues on all remaining work packages aiming for completion within 2020.

Vacutech has finalised the pneumatic drive series for SEM grids and scintillating screens detectors. A prototype detector pocket with thin vacuum windows is under construction. Brazing tests for the delicate connection of the foil window to the detector pocket were completed by successful leak test measurements. The FDR for the pneumatic drive for the particle detector combination is under preparation. If successful, the final drive type will be cleared for production at the end of May 2020.

For the industrial control system, a final design is established. Work on certification issues has started in preparation of the final design review. Production of small electrical parts is ongoing.

COSYLAB continues on the FESA class implementation for ring BPMs including the concentrator PC that represents the interface to the accelerator control system. Some of this work was adopted for the HEBT BPM specification, completed in April 2020. On this basis COSYLAB has drafted a software design document for the FESA class that is currently under review. The software upgrade of the stepper motor system is almost finished. For the completed driver upgrade the Site Acceptance Test is ongoing. After that, the Site Acceptance Test (SAT) for the upgraded FESA class with timing integration can commence.

#### *In-kind India:*

The new provider Vacuum Techniques Pvt Ltd. has delivered two prototype chambers in December 2019. The chambers were tested for their mechanical and vacuum properties according to technical guidelines. With conditional approval granted in January 2020 further cooperation with this new Indian partner looks promising.

## Vacuum chambers

In 2019 installation of the 51 vacuum chambers of batch1 for dipole magnets, manufactured by BINP, continued in parallel to delivery of magnets of batch1 by NII-EFA. Within total 37 chambers integrated in 2019, completion of installation of all chambers of batch1 is expected for the end of 2020 shortly after delivery of the last magnet of batch1.

In May 2019 a second contract with BINP for 272 vacuum chambers for the magnets of batch2 and batch3 was signed. Subsequently, the Conceptual Design Reviews of four work packages comprising vacuum chambers for different types of dipole and quadrupole magnets were successfully concluded in the second half of 2019. In addition, the first three vacuum chambers for dipole magnet dip13, a chamber type known from batch1, were already manufactured. The final acceptance test (FAT) of these chambers is planned for spring 2020.

Furthermore, another contract with BINP (HEBT vacuum chambers batch4), comprising pumping chambers, straight tubes, bellows etc. was signed in November 2019.

## psp 2.14.1 Electric Power (Power connection to FAIR/Campus (EP))

### Power Connection to FAIR

The new FAIR transformer stations have been operating in very reliable operation since the beginning of 2018.

Transformer Station North, which offers operation of up to four 20kV outputs, supplies at the moment only the SIS18/ESR pulload. The Transformer Station South started to offer operation of up to five 20kV outputs. At the moment transformer station south supplies 20kV for FAIR construction site. In order to improve the power quality in the existing GSI, an additional 20kV feeding into the GSI 20kV-grid started in October 2019 to supply power to the GSI "Green IT Cube" high performance computer.

These two FAIR transformer station projects are now completed.



Figure 62. FAIR Transformer Stations North (top) and South (bottom).

### Machine cable management and User Cable

All cable related information (excluded the earthing cabling and machine cable trays) is collected in a cable database controlled by the cable manager. A comprehensive update including supplementation by the required cable connectors was performed in 2018/2019. All information was delivered to FAIR S&B and the planners as basis for cable procurement beginning of April 2019. The first check concerning the cable amounts and volume of the “short text” LV, was executed in the end of 2019 as well as a kick-off meeting concerning the cable routing.

Delivery of power cables is foreseen via an Indian in-kind contribution, a first meeting with the Indian partner took place to discuss all steps of procurement process including delivery to FAIR.

### psp 2.14.8. Cryogenics (CRY)

The technical department Commons Cryogenics (CRY) is responsible for the GSI and FAIR wide cryogenic helium cooling 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 R<sup>3</sup>B GLAD magnet testing as well as for the cooling of the CRYRING electron cooler solenoid. The main future consumers 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.

### 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. In the first instance a 19 kW @ 4 K equivalent Cryo plant will be installed, including a campus wide 1.6 km long distribution system. For 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 was ordered in one lot, the purchase order has been placed at the end of October 2019 with the company Linde Kryotechnik AG.

### 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 distribution system. After approval of the specification in the second quarter in 2019, the SIS100 distribution system was ordered from Demaco Holland B.V. and is presently in production.

### psp 2.14.10. Control Systems (ACO)

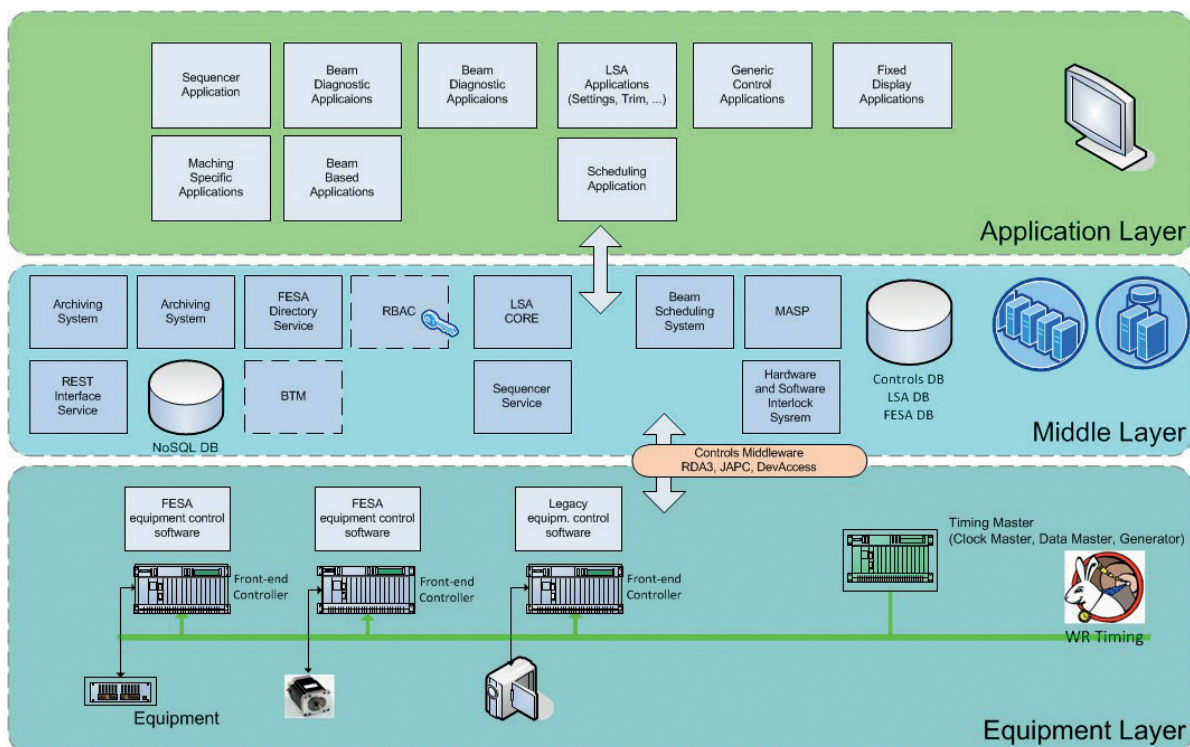


Figure 63. FAIR control system stack.

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, but UNILAC excluded).

After a 2-year long shutdown in 2016-2018, a basic version of the full stack of the new control system to fully replace the technically obsolete existing system has been developed, rolled out, commissioned in June 2018 and successfully used for the user beamtime in early 2019. Compared to the situation of the engineering beam time in December 2018, the stability of the control system was substantially improved.

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.

In parallel to continuing development of FAIR-specific equipment control implementations, the activities of the Controls development team is presently fully focused on the implementation of a dedicated storage ring functionality as needed for FAIR Phase-0 operation in ESR and CRYRING (e.g. beam time in early 2020) and for future use in CR and HESR for the full FAIR facility. The storage ring functionalities will allow to interactively execute stop points, multiple beam manipulations, repetitions and skipping of beam processes while beam is in the machine.

Moreover, significant progress has been made in the past months 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. The first 400 SCU units out of 1200 units (for MSV 0-3) have already been produced, of which 100 units are already in-installed and operated in the existing machines. Production and assembly of 200 units more (of the first batch of 600) is presently ongoing. Due to already obsolete electronic components, a planned redesign of the SCU unit has been started and a first prototype is already under development and component testing in the laboratory (SCU4 project).
- Electronic timing receiver boards (FTRN) in several form factors (PCIe, VME, PMC, uTCA), both GSI in-house developments as well as Slovenian In-kind contribution projects, are under development. Form factors uTCA and PMC have been fully developed, successfully passed integration and acceptance test and are presently under production by the Slovenian provider.
- Central components of the FAIR high-precision timing system to distribute and synchronise machine operation have been further developed and tested. This includes the central Data Master (timing director) as well as the White Rabbit protocol-based timing network switches. After intensive testing, the procurement process for all WR switches has been started and the contract to deliver all WR switches for the full facility has been successfully awarded to two companies. Delivery of the full set of switches is expected completed until end of 2021.
- 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. To fully control storage rings in interactive mode, specific functions (stop points, repetitions, manipulations and skipping of beam processes) are presently integrated in the core LSA system.
- Development on the accelerator measurement and data archive system is being continued by the Slovenian In-kind partner; after successful evaluation to confirm the technology choices, a first prototype system has been deployed and operated during the user beam time in early 2019, taking first data under real-life conditions. SAT approval will be performed until Q3/ 2019.
- On the industrial controls side, vacuum control with the industrial control SCADA-based UNICOS framework has shown to be a reliable and robust solution at the CRYRING machine in the past 2 years. Presently a modernisation of the UNILAC vacuum control system is done until November 2019, implementing the UNICOS vacuum standard as a model for the p-Linac.
- In respect of cryogenic controls, several cryogenic sensors and actuators have been tested as a sound base for the cryogenic controls system design. Control cabinets for the testing of FAIR cryogenic magnets have been successfully designed, produced, delivered and commissioned for the Super-FRS magnet testing at CERN.
- New prototype operator consoles for the future FAIR control center (FCC) have been de-signed, installed and used for operation of the GSI accelerators. A set of basic and generic new Java-based control room applications have been developed and deployed for operator and machine specialists. Furthermore, prototype fixed displays as foreseen for the FCC have been mounted and put to operation with a first set of fixed display applications.
- Efficient tools for diagnostics, testing and measurement data acquisition for FAIR hardware and beam commissioning have been developed or are presently under development (Diagnostic logging, Archiving, Sequencer, etc.). A dedicated technical system for digitisation of analog signals by the control system has been fully developed.

- It is presently under production and already partly rolled out for SIS18 for operational testing. The implementation of a powerful continuous integration system has been started, this system being a valuable testbed for new control system functions.



Figure 64. High quality digitizer systems.

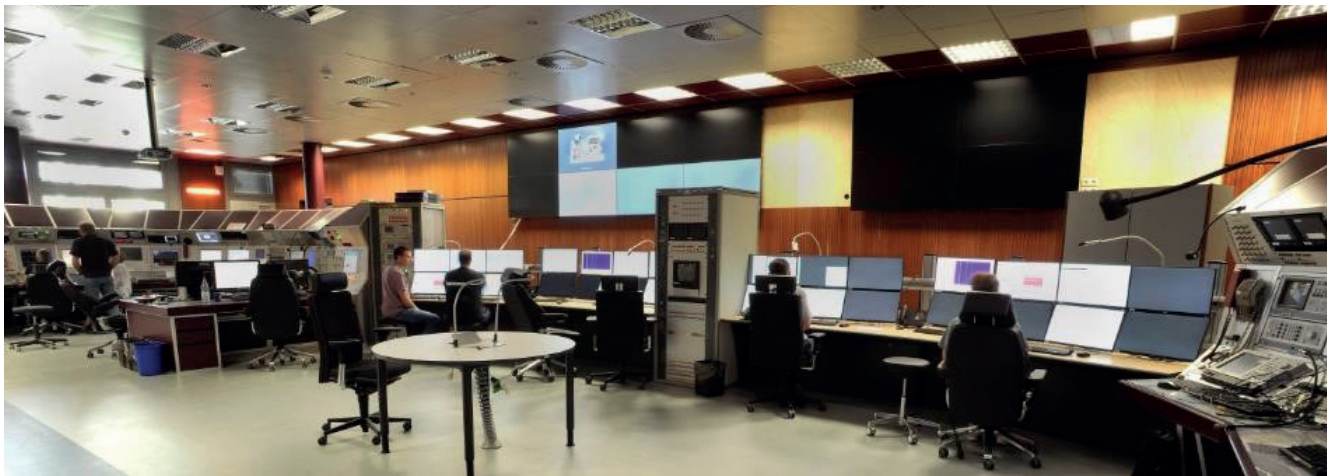


Figure 65. GSI control room refurbished with new FAIR consoles and fixed displays.

### psp 2.14.12 Transport and Installation (TRI)

Beside supporting the Accelerator Operation Division in service, reconstruction and upgrade of accelerator components during the presently running shutdown and for preparing the planned beamtime program, TRI is, together with the Logistics-Team from Procurement Department, strongly involved in the development of strategic logistics concepts for transport, component testing e.g. the SIS100 Dipole- Testing program, intermediate storage and delivery.

Another aspect now getting in focus is the further development and detailing of the installation plans created in 2016 driven by Site Management / Machine Installation and the preassembly activities of already delivered FAIR components, especially NCM Magnets for HEBT.

## 14. Operations and Accelerator R&D

Head: Prof. Dr. Mei Bai, GSI

Authors: Mai Bai and Giuliano Franchetti

Focusing on the FAIR Phase-0 research program as well as on upgrading of the existing accelerator facilities in particular UNILAC, and critical infrastructures such as Galvanic workshop, the Accelerator Operation department (ACC) successfully performed the beam times planned for 2019, i.e. a dedicated physics run of the FAIR Phase-0 program in the 1<sup>st</sup> half of 2019 and the 2<sup>nd</sup> engineering run during the last quarter of 2019.

The summer shutdown of 2019 was allocated to address the major technical issues that were identified in the 2018 beam time: the replacement of the electrodes and carrier rings of the radio frequency quadrupoles (RFQ) in the high current injector (HSI) beam line, the ultra-high vacuum upgrade at the UNILAC, repair of the damaged power converter of the UNILAC single gap resonators that are required for fine energy adjustment for UNILAC experiments, and coordinating re-commissioning ESR as a storage ring and completion of CRYRING commissioning with ESR beam. These measures were essential in re-establishing the core capabilities of GSI facilities and fulfil the scientific scope of the FAIR Phase-0.

Major milestones have been reached during the 2nd engineering run, despite its rocky start due to unexpected technical interruptions:

- re-establishing the heavy ion beams like uranium through UNILAC to SIS18 for FAIR Phase-0 experiments
- re-establishing the storage ring mode with the FAIR accelerator control system LSA in the ESR

As result, an argon beam was decelerated in the ESR, then successfully injected and subsequently stored in the CRYRING.

HSI RFQ with replaced electrodes and carrier rings was also commissioned during the engineering run. Currently, 85% of the nominal required field for accelerating  $U^{4+}$  is reached with which more than  $10^9$  uranium ions were injected and accelerated in the SIS18. While further efforts are still needed to push the HSI RFQ to its nominal field for  $U^{4+}$ , we are able to fulfil the requirements of the experiments scheduled for 2020.

In addition to re-establishing the GSI facility core capabilities, i.e. high intensity heavy ion such as uranium beams, experiments at storage rings, and decelerated beam from ESR to CRYRING, a total of 36 dedicated beam studies/machine developments were also carried out during this engineering run.

ACC continues its commitments to the FAIR project in leading work packages of the p-Linac proton source, p-LINAC radio frequency, a 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 laboratory also continues its strong technical support across the campus. In particular, the galvanic workshop has successfully copper plated a demonstrator drift tube for the first-of-series module of the Alvarez upgrade. In order to further improve the coordination of the copper plating for various requests, i.e. the Alvarez post stripper upgrade and the p-Linac, an integrated planning of copper plating has been developed for the best interest of the overall GSI/FAIR strategic goals.

## 14.1 User Beam Time Report

Authors: S. Reimann, O. Geithner

The 2<sup>nd</sup> Physics Run within the FAIR Phase-0 started on February 19<sup>th</sup>, after a short winter shut-down, a long conditioning period for the UNILAC-HF of 4 weeks and a short recommissioning phase.

Due to the limitations of the mass-to-charge ratio caused by the damaged HSI-RFQ, the planned heavy ion operation of lead and uranium had to be abandoned. At UNILAC, tin, carbon and silver beams were offered for biophysics and materials research, initially, followed by a longer block of calcium-beam, provided for the super heavy elements program and iron for biophysics.

At the SIS18 also carbon for biophysics was provided first. Afterwards tin-beam was delivered for Cave-C.

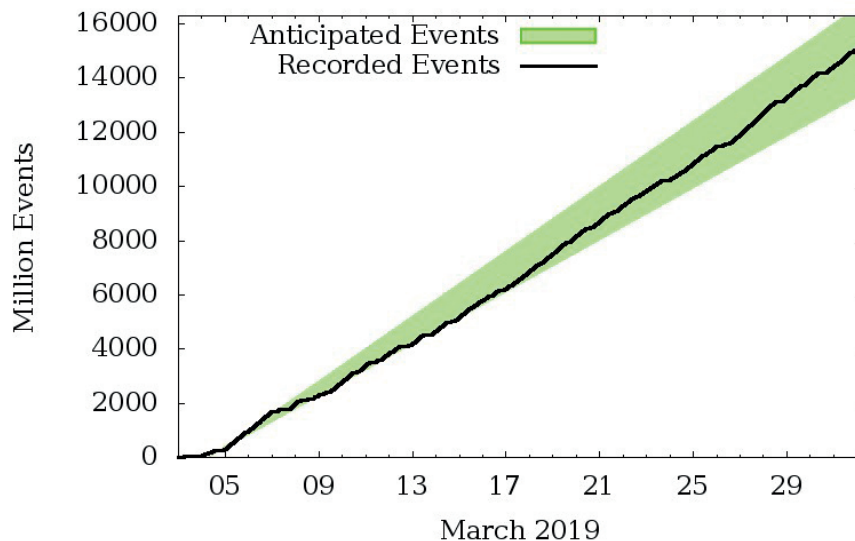


Figure 66. Number of events recorded by the HADES experiment during beam time 2019.

The biggest challenge during this beam time was the HADES experiment with silver ( $^{107}\text{Ag}$ ). The experiment required a high-intensity silver beam, stable over 4 weeks with a micro-spill-structure as uniform as possible over the very long extraction time of up to 20 s. Several days were invested for setup and adjustment, and after all this efforts, the necessary number of events required for this experiment could be recorded in the end (see Figure 66).

In April, oxygen beam was provided for  $\text{R}^3\text{B}$  experiment. Unfortunately, the requirements for the micro-spill-structure could not be met in the short time available. Further investigations on this topic were then carried out in the engineering run at the end of the year.

Most of the other planned experiments could be satisfactorily supplied with the requested nominal beam parameters during the beam time, not least due to the high availability of all accelerator sections, which is also reflected in the statistics.

## Statistics

In physics run 2019 (19.2 – 15.4) the following projectiles were delivered:

Source	Ion	Delivery (hours)
UNILAC PIG	$^{120}\text{Sn}^{5+}$	167.45
UNILAC PIG	$^{56}\text{Fe}^{3+}$	182.98
UNILAC PIG	$^{197}\text{Au}^{8+}$	606.75
UNILAC Varis	$^{16}\text{O}^{1+}$	165.18
UNILAC Varis	$^{107}\text{Ag}^{3+}$	891.13
UNILAC ECRIS	$^{12}\text{C}^{2+}$	161.55
UNILAC ECRIS	$^{48}\text{Ca}^{10+}$	573.0
UNILAC ECRIS	$^4\text{He}^{1+}$	72.53

Table 2. Ions species used during the accelerator beam time in the physics run (February- April 2019).

Source	Ion	Delivery (hours)
UNILAC PIG	$^{40}\text{Ar}^{2+}$	464.0
UNILAC PIG	$^{40}\text{Ar}^{1+}$	471.42
UNILAC CHORDIS	$^{40}\text{Ar}^{1+}$	516.2
CRYRING MINIS	$^{12}\text{C}^{1+}$	831.5
UNILAC VARIS	$^{238}\text{U}^{5+}$	244.78
UNILAC VARIS	$^{238}\text{U}^{4+}$	138.58

Table 3. Ions species used during the engineering run (November- December 2019).

The physics run was scheduled from 21. February to 15. April. An overall availability of the accelerator of 91% was reached, as can be taken from the diagram in Figure 67. The engineering run was scheduled at the end of the year (11. November to 20. December). The main goals were the commissioning of the storage ring mode supplied by the accelerator control system as well as to inject beam from ESR to CRYRING and store it. Both goals have been achieved.

The availability during an engineering run (see Figure 67) is usually worse than during user beam time. One reason is that the failure rate during initial setup is always higher than in a stable operation mode. In this engineering run, general setup and accelerator settings were frequently changed completely, which is quite different from a standard user beam time. The times for setup and adjustment are also slightly overrated for this reason.

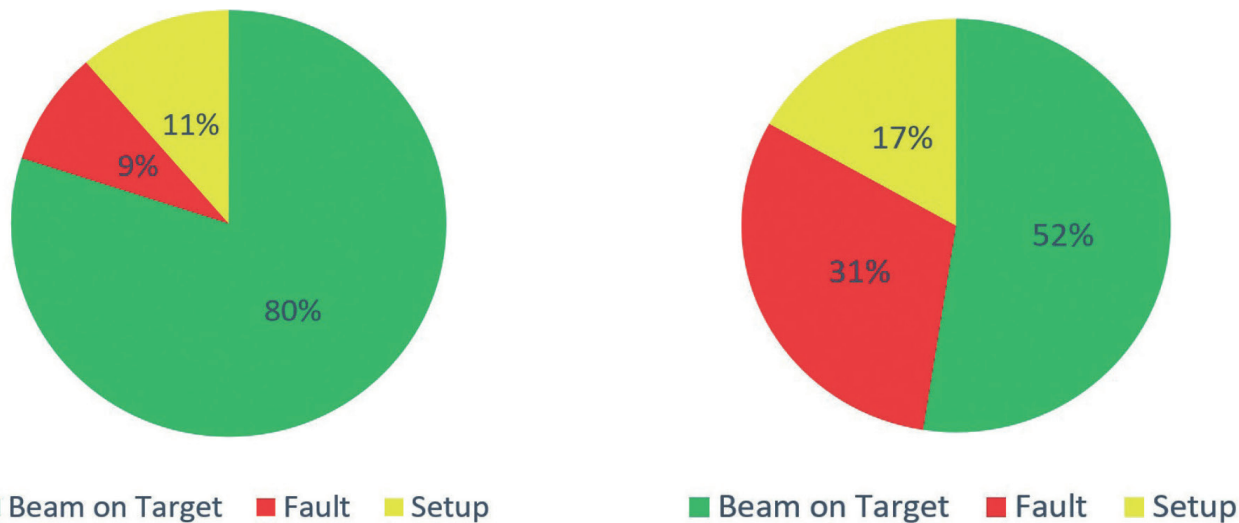


Figure 67. General event statistics of the Physics Run 2019 (left) and the engineering run (right)..

Nevertheless, the engineering-run suffered from several major failures especially during the first week. Several high-impact failures have been identified:

**LINAC RF:**

- Heater power supply failed (total impact 120.65 h)
- Cannot reach uranium level (Gauge) (total impact 425 h)

**Vacuum Leaks:**

- Experiment chamber in CRYRING (total impact 323 h)
- UNILAC UH4 Region: no root cause was identified. It was stabilized on its own, causing permanent external interlocks and further failures in this region (total impact approx 122 h)

**Controls:**

- major bug of the timing system caused faulty ramps in SIS18 power supplies. Due to the complexity of the bug, it took 5 days to find the cause.

An Availability Working Group (AWG) was organized, which followed on a weekly base all faults in the operation logbook OLOG and assigned correctly the Fault Root Causes. Hence, the Table 4 presented below contains the fault statistics of the engineering run, which is verified by the expert groups:

Root Cause System	Duration (hours)	Number of failures
LINAC RF	552,02	16
Vacuum leaks	448.97	47
Vacuum	341,40	5
Controls	190,73	46
Beam diagnostics	153,27	5
Power supplies	83.72	5
Injection/extraction	58.05	12
LINAC	48.53	17
Decelerators	47.42	1
Operating	39.90	4
Miscellaneous/unclear	14.87	5
Interlock/safety	5.40	5
Infrastructure	4.48	7
Ring RF	3.52	7
Ion sources UNILAC	3.27	7
Basic-IT	2.22	1
Magnets	0.27	2

Table 4. Breakdown statistics of the engineering run.

### 14.1.1 Ion source operation report

Authors: A. Adonin, R. Hollinger, K. Tinschert

In 2019 the ion source department provided various types of ions for a user beam time as well as for an engineering run. The high current ion sources (CHORDIS and 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 accelerator in parallel operation. Table 5 gives an overview of the ion species, delivered to the accelerator. Representative values of intensities are the analyzed beam currents in front of the HSI-RFQ and of the HLI-RFQ, respectively.

The most requested ion species from the Penning ion source during the physics run was gold ( $^{197}\text{Au}^{8+}$ ) for materials research (UMAT) and for plasma physics experiments. The PIG source was operated with high duty cycle (50 Hz / 3-4.5 ms) with electrode lifetimes of approximately 24 hours.

The ECRIS at the HLI was in operation for physics experiments.  $^4\text{He}^{1+}$  and  $^{12}\text{C}^{2+}$  were provided for biophysics experiments, while  $^{48}\text{Ca}^{10+}$  was used for runs of the Super Heavy Element (SHE) programme.

The highlight of the user beam time in 2019 was a high current operation of the VARIS source with  $^{107}\text{Ag}^{3+}$  ion beam from natural silver. That was the longest Ag beam time (38 days) for the last decades. The first operation experience was gained with 3+ ions providing a record intensity of 3.5 mA  $\text{Ag}^{3+}$  in front of the HSI RFQ. Moreover, the whole beam time was performed with a single ion source without interruption due to ion source service.

Another highlight, achieved in the engineering run, was establishment of a new operation mode for uranium. It was possible to maximize the production efficiency of  $\text{U}^{5+}$  ions in the VARIS plasma resulting in an intensity of up to 6 mA in front of the HSI RFQ.

	Ion	Duty cycle	Intensity (RFQ/emA)	Source	Duration (days)
Physics Run	$^4\text{He}^{1+}$	cw	0.41	ECRIS	2
Physics Run	$^{12}\text{C}^{2+}$	cw	0.085	ECRIS	14
Physics Run	$^{32}\text{O}^{2+}$	1 Hz/ 0.8 ms	5	VARIS	8
Physics Run	$^{40}\text{Ar}^{2+}$	50 Hz/ 3 ms	0.3	PIG	6
Physics Run	$^{48}\text{Ca}^{10+}$	cw	0.07	ECRIS	24
Physics Run	$^{56}\text{Fe}^{3+}$	5 Hz/ 1 ms	0.08	PIG	6
Physics Run	$^{107}\text{Ag}^{3+}$	1 Hz/ 0.4 ms	3.5	VARIS	38
Physics Run	$^{120}\text{Sn}^{5+}$	5 Hz/ 1 ms	0.04	PIG	17
Physics Run	$^{97}\text{Au}^{8+}$	50 Hz/4.3 ms	0.04	PIG	24
Eng. Run	$^{40}\text{Ar}^{1+}$	2 Hz/ 0.5 ms	20	CHORDIS	25
Eng. Run	$^{40}\text{Ar}^{1+}$	5 Hz/ 1 ms	0.8	PIG	10
Eng. Run	$^{40}\text{Ar}^{2+}$	10 Hz/ 2ms	0.3	PIG	30
Eng. Run	$^{238}\text{U}^{5+}$	0.5Hz/0.25ms	5	VARIS	19

Table 5. Ion beams provided by high current and ECR ion sources for physics and engineering runs in 2019.

## 14.1.2 UNILAC report

Author: H. Vormann

### Operation and related works

In 2019 the UNILAC was in operation 60 days of user beam time (15<sup>th</sup> February to 16<sup>th</sup> April 2019) and 45 days during an engineering run (4<sup>th</sup> November to 19<sup>th</sup> December 2019).

The beam time was dominated by high-current beams of  $^{107}\text{Ag}$  (VARIS) for the SIS18 synchrotron, and high duty cycle beams of  $^{197}\text{Au}$  (PIG) and  $^{48}\text{Ca}$  (ECR) for experiments at the UNILAC. Furthermore,  $^{16}\text{O}$  (MUCIS) was delivered to the SIS18 synchrotron. The PIG provided  $^{40}\text{Ar}$  for the early re-commissioning of the full chain of accelerators, and  $^{120}\text{Sn}$  and  $^{56}\text{Fe}$  for UNILAC-users and the synchrotron SIS18 as well. The ECR delivered  $^{12}\text{C}$  to UNILAC and the SIS18 synchrotron and  $^4\text{He}$  for biology experiments supplied by UNILAC.

The beam time schedule took into account the restricted performance of the HSI RFQ (max. voltage 6.2 volts). The performance degradation, observed after long shutdown during set up for beam time 2018, could not be improved in a short time, because new electrodes had to be manufactured first (manufacturing from September 2018 to February 2019). In the shutdown 2019, the severely affected RFQ electrodes were replaced by new ones. Nevertheless, during recommissioning the RFQ reached at the maximum 87% of the nominal voltage level of 8.3 volts, which was not unexpected in 2019, taking into account the relatively short time available for conditioning the new rods. Note: the RFQ is still under conditioning.

We replaced the thick walled beam tube of the quadrupole quartet in front of the HSI RFQ (UH-2QQ1) by a thin walled tube with reduced aperture (144 mm / 100 mm) to reduce eddy currents. Machine experiments performed on the QQ recommissioning after replacement of the beam tube, confirmed that for proper focusing the same magnet settings as before should be used.

Special investigations on HSI Uranium beam-operation with  $\text{U}^{5+}$  (requested RFQ voltage of 6.6 Volt) and – after further conditioning – with  $\text{U}^{4+}$  at an RFQ voltage of 7.1 Volt (85% of nominal  $\text{U}^{4+}$  value) were carried out successfully during the engineering run.

Note on the year 2018: The 2018 beam time had been shortened (11<sup>th</sup> June to 14<sup>th</sup> July 2018), due to a failure of the new ventilation system of the UNILAC RF gallery, causing severe damages in the power supply for the single gap resonators and in the whole gallery. In addition to that, a significant performance loss of the HSI RFQ was recognized after the 2017 shutdown, high RF levels were not possible. As a fast repair of the power supply was not possible until autumn 2018, the second part of the beam time 2018 was replaced by an engineering run, starting on 5<sup>th</sup> November 2018, ending on 16<sup>th</sup> December 2018 (RF commissioning from 8<sup>th</sup> October on).

### 14.1.3 SIS18 operations

Author: J. Stadlmann

SIS18 was operated during two blocks in 2019. The first block was dedicated for experimental user beam time for FAIR Phase-0 experiments. The second block was an engineering run to test and establish operation modes for the user beam time in 2020.

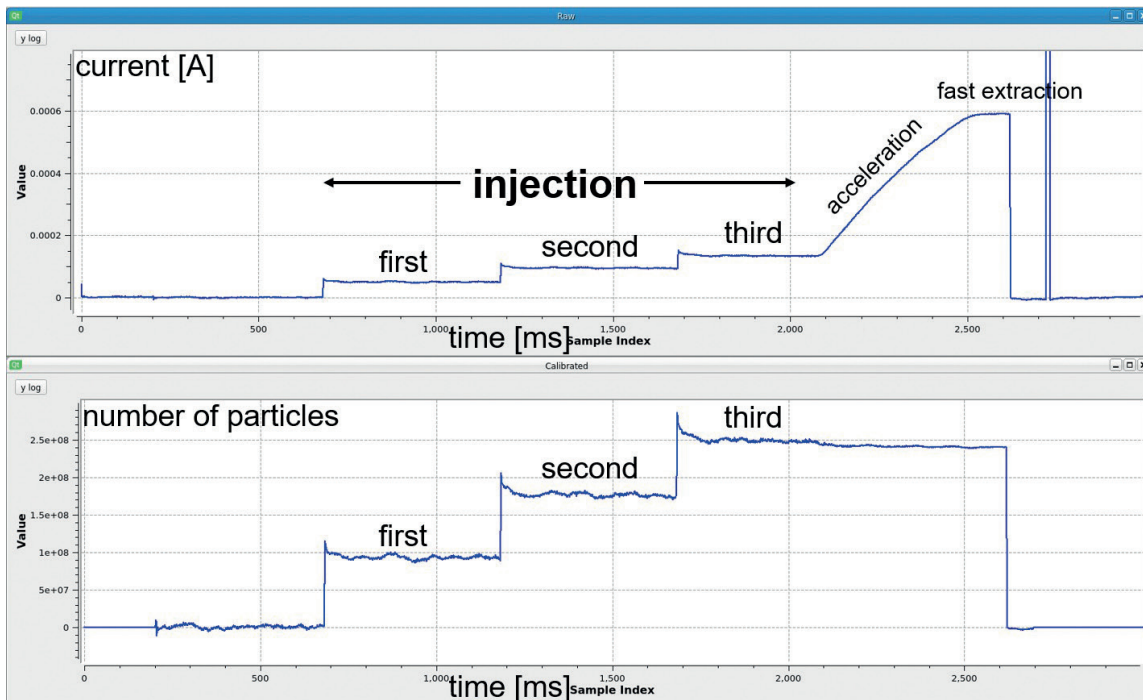


Figure 68. The transformer signal and calculated particle number during one machine cycle with Multi-Multiturn injection. Three injections from the UNILAC are accumulated with SIS18's electron cooler and accelerated and extracted with fast extraction.

This was the first user beam time running with the new control system, timing system and data supply, which will become the FAIR accelerator control system. During the 2019 beam time, we could operate SIS18 in all modes and capabilities which were possible with the previous system. The last mode of operation established, was the accumulation of several beam injections from the UNILAC with the electron cooler (Multi-Multi turn Injection, see Figure 68).

The new control system allows for more flexibility in SIS18 operation. One example is the utilization of lower injection energies from UNILAC, which was necessary due to planned work on the last Alvarez stages of the injector. The low injection energy does not normally allow to capture and accelerate the injected ions with the standard acceleration cavities with the design harmonic number of  $H=4$ . The reason is that the cavities cannot operate with the required low frequency. To mitigate this obstacle, we used to operate SIS18 with higher harmonic numbers of  $H=5$  or  $H=6$ . We were thus limited in maximum achievable extraction energy due to the upper frequency limit of the acceleration cavities. However, with the new  $h=2$  RF cavities installed in the course of the SIS18 upgrade for FAIR (see [3,4]) we are able to capture the ions after injection with harmonic number  $H=4$  and start acceleration. Due to the flexibility of the new control system and data supply it was possible to handover the acceleration to the regular  $H=4$  cavities on the ramp and continue acceleration to full energy (See Figure 69).

This mode was established and used for regular operation to deliver beam to various experiments and engineering run tests. This mode is an impressive performance test of the synchroni-

zation system between the RF cavities, which is essential for the dual harmonic operation which is foreseen for the operation of SIS18 as FAIR injector.

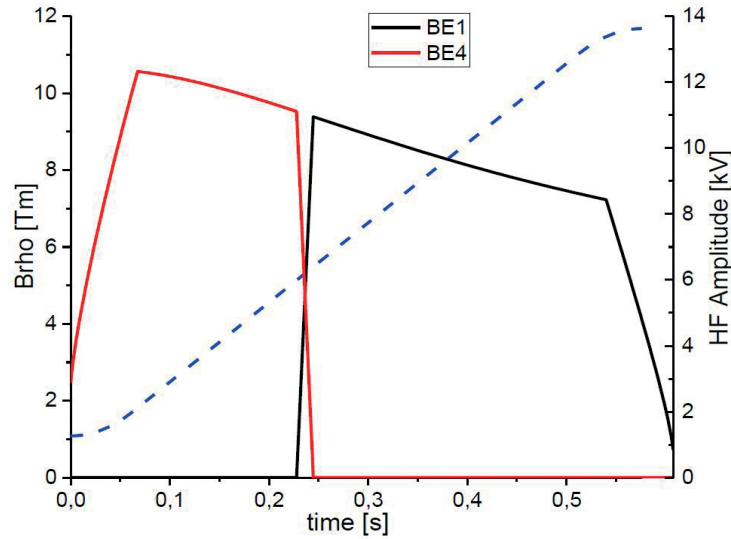


Figure 69. The RF amplitude ramps of the H=2 system (BE4, red) and the H=4 system (BE1, black) during an acceleration ramp (magnetic field of main dipole in blue dashed) from very low injection energy (8.6 MeV/u instead of 11.4 MeV/u) to maximum extraction energy. The synchronization of the systems which is normally needed for dual harmonic operation allows for the handover during acceleration. Both systems were operated on H=4.

The new accelerator control system LSA is still in a very premature stage of development and the overall performance was good. However, the usability for beam settings and operation was massively impaired by extremely slow response times for setting changes (trims) of up to one minute. That does not affect the performance for running experiments but considerably increases the required setup and tuning times for all experiments. The problem is addressed by the development team starting in 2020.

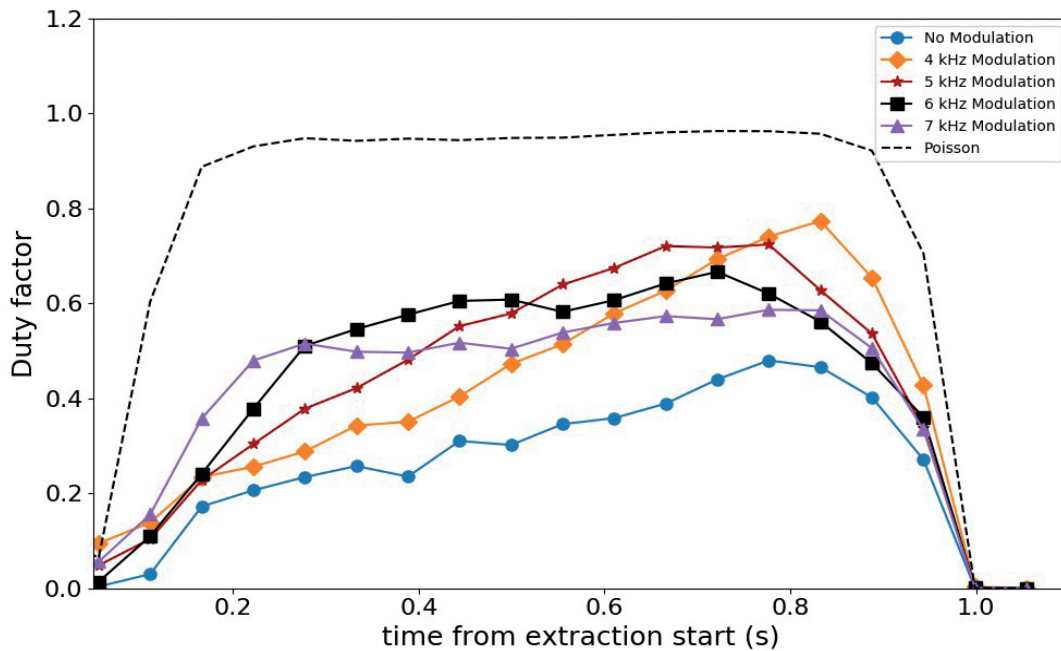


Figure 70. Duty factors of quadrupole driven slow extraction of Ar18+ beams at E = 300 MeV/u for various fixed frequency tune modulations.

One major success during the 2019 user beam time was the development of a method for smoothing SIS18's slow extraction micro spill structure (Ref 5). The improvement was established by modulation of a high frequency (4kHz to 7kHz) disturbance onto one of the main quadrupole

power circuits of SIS18 during resonant slow extraction (see Figure 70). The method was tested during the engineering run 2018 and could successfully be used in single user mode for the HADES user beam time 2019 increasing the effective average beam intensity for the experiment by about 50%. The required hard- and software has meanwhile been integrated into the control system and is available for regular operation in 2020.

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## 14.1.4 HEST setting management and Engineering Run 2019

Authors: C. Hessler and M. Sapinski

Since 2018 the HEST beamlines are operated with the new control system LSA, used also to control SIS18, ESR and CRYRING. LSA provides a data base for storage of optics settings in internal tables. Those tables are prepared based on specially formatted files, which contain information about magnet strengths and the theoretical Twiss parameters. One or two of such optics per beam line are stored in LSA. They are called STANDARD setting, if they originate from baseline MIRKO files stored in a subversion repository, or LEGACY setting, if they originate from settings nested in the front-end electronics of the former control system. In addition, the files used to create those LSA settings are stored in version-control systems (subversion and git) on the GSI accelerator computing cluster. For clarity and because setting up an optics in the LSA database is a complicated process, it was decided to keep the number of LSA optics per beam line small (currently two). In general, one well-optimized optics for each beam line should be sufficient, once it has been established.

For changing the magnet settings, e.g. to adapt the optics or to steer the beam, the ParamModi control application is used. This application allows entering the top-level parameters, like e.g. the quadrupole strength K1L, in text input fields for each magnet.

Good settings obtained after fine optimization of the machine are regularly saved with the ParamModi application in its native file format. Those files are often attached to Logbook entries and saved by operational team and experimentalists for further reference.



Figure 71. Screenshot of the new control application showing the envelopes of the SIS18\_TH\_HTP beam line.

In the old control system, it was possible to change the optics and steering comfortably by mouse click with the Mirko Expert application, which however is not available in the new control system anymore. The development of a new control application providing this feature has started in 2019. It displays the beam envelopes calculated from the actual machine settings (Figure 71) and allows changing the envelopes and trajectories by mouse click and sending the updated settings to LSA. Technically, it uses the MAD-X beam dynamics simulation code for envelope calculation, with which it communicates via the JMad Java API. The information on the beam line model used by the new application is stored in a git repository and directly fetched by the application.

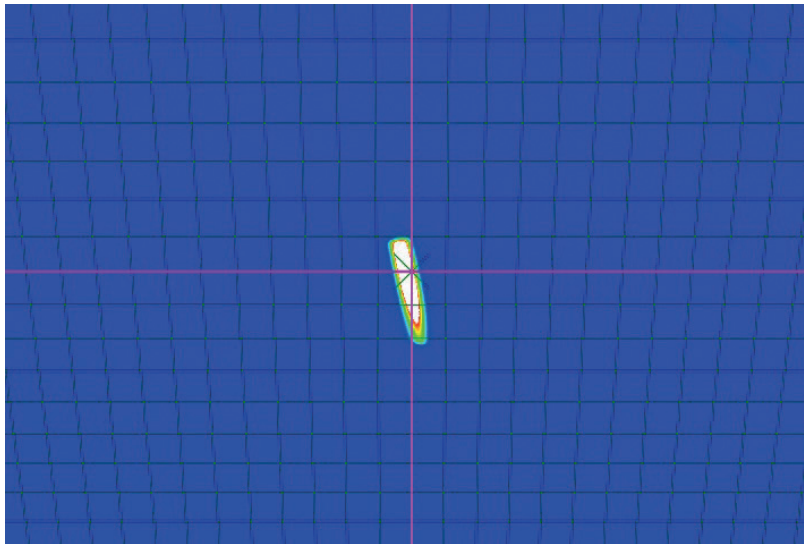


Figure 72. The image of the beam on the last scintillating screen before injection into Cryring. Due to the lack of time and the high latency of the trim process in LSA, the beam transport could not yet been fully optimized, resulting in a partially cut beam profile on the screen.

A highlight of the 2019 engineering run was the transport of decelerated  $40\text{Ar}^{18+}$  beam from ESR to CRYRING. The beam was transported between the two storage rings for the second time ever, and it was the first time using LSA. Figure 72 shows a beam image on the last scintillating screen in the beam line in front of the CRYRING cave.

During the engineering run 2019, a follow-up machine development study of the campaign to measure the transfer line optics in engineering run 2018 was performed. The goal of this study was to measure the emittance of the slowly extracted beam for different sextupole settings, by using the quadrupole scan method. The analysis of the data taken during this shift is currently ongoing.

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### 14.1.5 CRYRING@ESR report

The standalone experiment E129 “Photoionization of  $\text{C}^+$  ions at CRYRING”, which was approved by the G-PAC in 2017, was scheduled in September 2019 with 30 shifts. For this a  $^{12}\text{C}^+$  beam was prepared using the MINIS ion source and 10 shifts have been delivered to the experiment with about  $5 \times 10^6$  particles in the ring, which was slightly less than required. The electron cooler was not available, hence only uncooled, but accelerated beam was delivered before the experiment ended prematurely due to a vacuum incident at the experiment’s detector.

## 14.2 Shutdown activities

Author. P. Schuett

During the shutdown between physics and engineering run, the accelerators were shutdown for maintenance, repair and upgrade measures.

The coordination process during shutdown was the same as in the previous years. In weekly meetings with the machine coordinators and representatives of all involved departments, we monitor the actual progress, discuss pending work and critical incidents and adapt the overall schedule accordingly.

Two large projects at the UNILAC were finished successfully.

- exchange of HSI RFQ electrodes and carrier rings (see M. Vossberg in this report)
- refurbishment of UNILAC vacuum controls

The modernization of poststripper Rf systems, which started in 2015, was continued. This project comprises a prototype Thales power amplifier for Alvarez 4, refurbishment of control racks and new high voltage power supplies. This project was again impaired by outstanding works on the ventilation of the RF systems (LA16) and by construction work on the roof of the RF gallery. Nevertheless, the UNILAC-RF department successfully commissioned the Thales power amplifier and thus, it is available for beamtime 2020.

Final acceptance tests of the civil construction projects were still outstanding. The nitrogen fire-extinguishing system for the SIS18 tunnel passed the official test by the authorities. A continuing issue is rainwater penetrating into the kicker installation room and a staircase and the elevator building in the inner part of the SIS18 ring tunnel.

The second of three big cranes in the SIS 18 target hall (TR, EX, and TH) got a modernized control system. This became necessary, because spare parts for the old system are no longer available on the market. Therefore, the crane was unavailable for four weeks during shutdown.

In 2018, a major aging problem in the large FRS dipoles forced us to renew the retention system of the coils. The repair went on in 2019 and was finished in time to start with commissioning during the engineering run.

A major upgrade of the accelerator control system was necessary to provide a storage ring mode for the ESR. The commissioning of the upgraded controls system was a major goal of the engineering run.

A vacuum problem at a diagnostic device in the extraction section – at the beginning of the extraction beam line of SIS18 - was finally solved.

Two installations related to SIS18 operation were finalized

- new ionisation profile monitor (IPM) at SIS18
- replacement of the chopper in the transfer channel (TK)

Due to a lack of time and work force resources, we postponed several installations:

- new switching magnet GTS1MU1, which will steer the extracted beam from SIS18 either to the fragment separator, to the experimental hall or to the upcoming SIS100
- the ultra-high frequency cavity for smoothing of the spill structure

## 14.2.1 HSI RFQ electrode exchange

Author: M. Vossberg

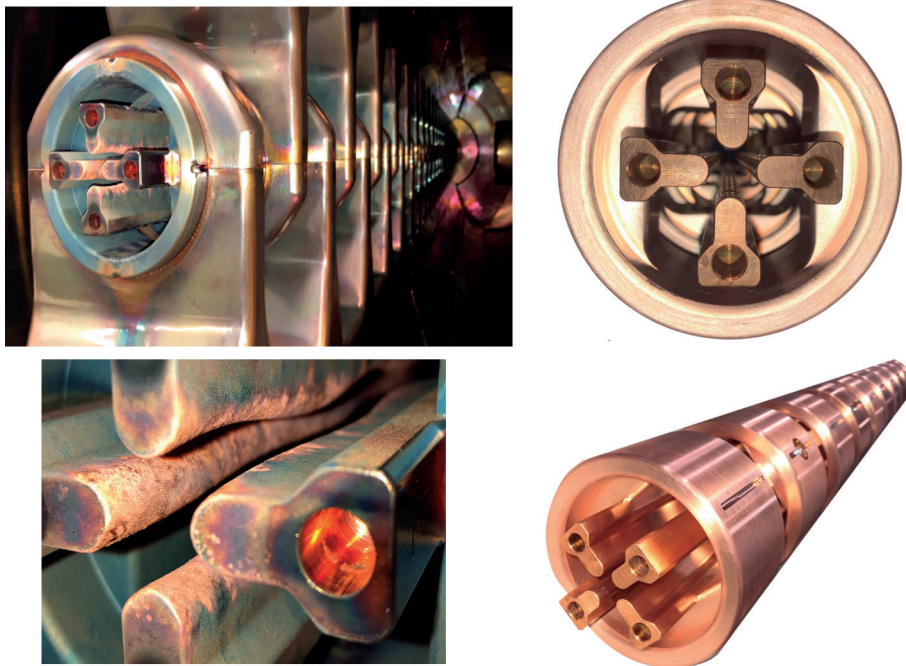


Figure 73. HSI RFQ after 2019 beam-time with the damaged surface of the electrodes and carrier rings (left side), and an electrode basket with re-produced electrodes and carrier rings (right side).

During re-commissioning for the beam time 2018, the HSI-RFQ did not reach its nominal voltage. For uranium beam, an internal scaled tank voltage of 8.3 V is required. Several investigations into the HSI-RFQ voltage drop were carried out, but the cause for the performance loss of the RFQ is still not completely understood, but most likely due to the expired lifetime of the electrodes, that have been in operation since 2009, in combination with Impurities and reactions on the copper surface due to moisture. To minimize the risk for operation of the next beam times a short-term solution has been carried out and it was decided to re-produce the RFQ-rods with the 2009 design. The reproduced electrodes were fabricated at the GSI workshop, in February 2019. For reasons of time, the decision was made that the new electrodes should not be copper-plated. In addition, new carrier rings were ordered from an external company. For all tank sections the completion of the electrode „baskets“ (with carrier rings) finished in April 2019. The removal of the old electrodes and the adjustment of the new ones started in the middle of May.

In July after installing the electrodes, various measurements were carried out to check the field distribution and resonance frequency. For this purpose, a measuring stand was set up, with an additional capacity (bead) being pulled through the resonator. The so-called interference body causes a shift in the resonance frequency and thus enables the voltage distribution to be determined. The aim of this measurement is to obtain a flat voltage distribution with suitable settings.

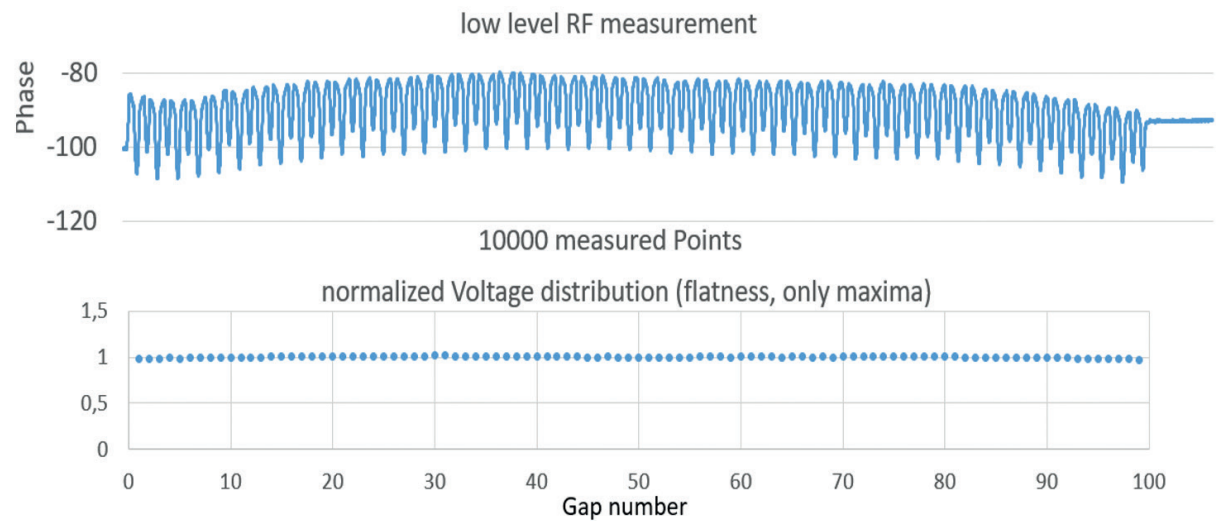


Figure 74. Low level RF measurement and the corresponding normalized voltage distribution. The field distribution inside the HSI RFQ is very stable and has only small changes by less than  $\pm 2\%$ .

The measurements showed an excellent voltage distribution, similar to the comparative measurements from 2009, and stable behavior. The plungers can also be driven without disturbing this distribution. After the RFQ was set back into the beamline, the tank conditioning started in September. Conditioning takes significantly more time with the new components. Nevertheless, a tank voltage of more than 84% of the nominal value could be reached by the start of the engineering run in November. By careful further conditioning parallel to the beam time, a voltage of 89% was reached by the end of 2019.

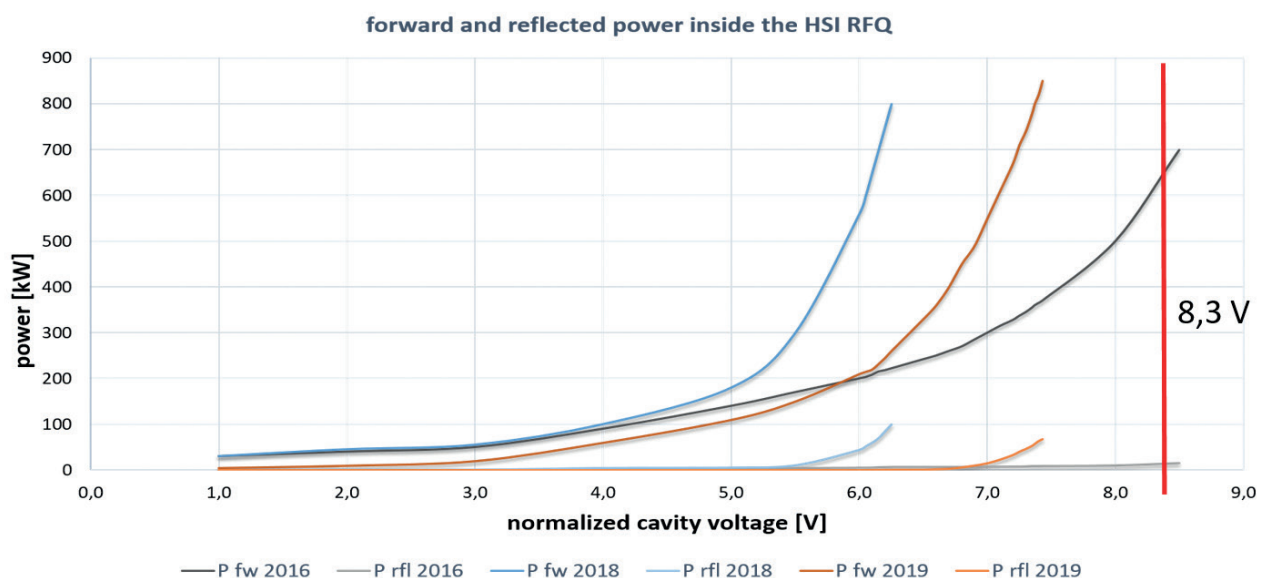


Figure 75. Measured forward and reflected power during 2016, 2018 and with the redesigned electrodes 2019. During re-commissioning 2018, the cavity voltage could not exceed a normalized value of 6.2 V. For uranium beam, a voltage of 8.3 V is required.

## 14.2.2 Follow up of the cryogenic transfer line to STF

Author: F. Dziuba



Figure 76. Picture of the new radiation cave for the advanced demonstrator at SH4 during construction (left) and after completion (right).

In 2019, the first of series cryogenic module for the new superconducting cw-Linac (HELIAC) has been defined and specified in more detail. According to the current planning, the cold part of the machine consists of four cryo-modules in total. Each module is equipped with three superconducting acceleration cavities and a rebuncher cavity as well as two superconducting solenoids for transversal beam focusing. The first cryo-module as well as all subcomponents are in preparation/production. It will be mounted behind the GSI High Charge State Injector at the cw-Linac test area serving as an advanced demonstrator for the new HELIAC. The upcoming full performance test of the advanced demonstrator with beam will be the next big milestone on the way building the complete superconducting cw-Linac. To realize stable 4 K operation of HELIAC, an appropriate cryo plant (240 W total cooling power required) for liquid He supply is necessary. The Series Test Facility (STF) with a corresponding 700 W cryo plant is already in operation for magnet testing. Here, the acceptance tests for the superconducting SIS100 dipole magnets are performed right now. After the magnet testing will be finished, the cryo plant is foreseen for operational supply of the HELIAC. In a first step, the company CryoWorld accomplished the extension of the STF infrastructure during Christmas shutdown 2018/2019. Afterwards, another company (DEMACO, Netherlands) has installed the link of the He-distribution system to the cw-Linac testing area in Q4 2019 (see Figure 77). The link provides helium at 4 K to the experimental test area and to the HELIAC. In this context, two additional valve boxes were installed and connected with four-fold vacuum isolated transfer-lines to the existing STF facility. Besides this, more infrastructure has been installed. A new radiation protection cave, housing the advanced demonstrator cryo-module, was finished in Q3 of 2019 (cf. Figure 76). At the same time, five rooms at the gallery of SH4 were renovated and rearranged. Two offices, a newly equipped electronic laboratory, a main control room with beam diagnostics controls, and a RF lab providing the required RF power by five solid state amplifiers are available for the next beam test of the advanced demonstrator. In Q2 of 2020 it is planned to build up the matching beam line from the high charge state injector HLI to the advanced demonstrator. First beam tests with the new cryo-module, which will be equipped with cavity dummy loads for that propose, and commissioning of the extended helium distribution system is scheduled for Q3 of 2020.



Figure 77. Installation of valve boxes (top) and liquid He transfer line (bottom) by DEMACO at SH4.

## 14.2.3 ER1 Power Supply Recovery and UNILAC RF Upgrade Progress

Authors: B. Schlitt, G. Schreiber, GSI



Figure 78. Left: ER1 1 MVA high-voltage power converter with 20 kV transformer (pulled out) during refurbishment. Right: New 1.8 MW Thales high-power RF amplifier and control racks (including PLC, grid power supplies, and further control and interlock components).

In July 2018, an electric arc occurred at the 20 kV main connections of the main transformer at the 1 MVA high-voltage supply feeding the RF power amplifiers of the UNILAC single-gap resonators. After the incident, the complete UNILAC RF gallery including all high-voltage supplies and RF amplifiers as well as the ducts of the air ventilation system were opened, cleaned, and inspected extensively in several steps. The main transformers of all 1 MVA power converters were pulled out of the supplies for inspection and cleaning (see Figure 78). While all other RF systems were recommissioned in 2018, the repair of the damaged ER1 supply was performed during 2019.

At ER1, various broken components and cables were replaced by spares or new parts, including parts of the internal and external air duct system. The 20 kV feeder line from the medium voltage power switching station was also renewed. High-voltage tests of all parts were performed before installation. Since the main transformer passed these tests successfully, it was reused. The power converter control electronics as well as all power circuits were carefully checked, tested and recommissioned step by step. Finally, RF operation of the single-gap resonators RF systems was re-established during the engineering run 2019 and all systems could be provided for user beam time 2020.

After installation and commissioning of the new LA16 air ventilation system for forced-air cooling of more than 60 high-voltage devices at the UNILAC RF gallery in 2017 and 2018, many measures were taken at the LA16 during the shut-down in 2019 for completion and for improvement. In addition, a major part of the RF gallery roof was renewed during that period. Further improvements of the LA16 and the completion of the roof renovation are scheduled during shut-down periods until the end of 2021.

A new microcontroller based resonant frequency control electronics [1] was successfully operated during routine operation at the Alvarez linac in 2018. In 2019, such systems were installed and commissioned also at all single-gap resonators and buncher cavities. Thus, the complete post-stripper linac is now equipped with new systems.

A PLC system for the new 1.8 MW Thales RF amplifier [1] was commissioned during 2018 and the amplifier was fully integrated into post-stripper operation. During 2019, the new amplifier and the PLC control were successfully operated during beam time for the first time. Very stable operation without major problems was achieved.

## Reference

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## 14.3 Engineering run

Author: Stephan Reimann

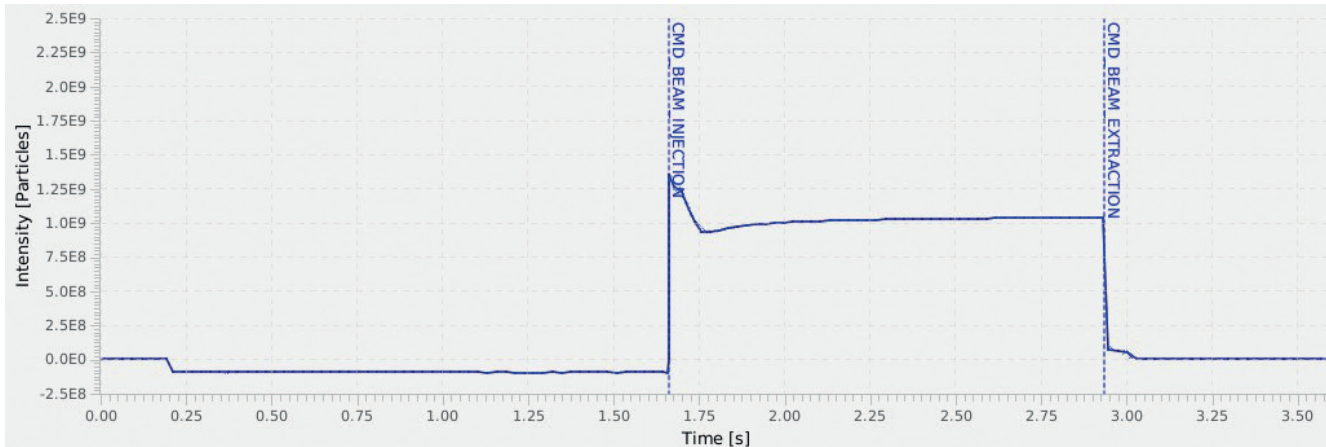


Figure 79. Particle flow in the SIS18 (uranium 68+), a maximum of 1.38E9 particles could be injected.

In preparation for storage ring operation, operation of the fragment separator and the heavy ion experiment program, which was scheduled for the beam time 2020, a dedicated engineering run was scheduled for the end of 2019.

After the replacement of the electrodes of the HSI-RFQ and the commissioning of the new Alvarez 4 power amplifier, additional time was needed by the UNILAC-RF for conditioning and further tests. The desired test time could not be fully provided because of delays in the construction of the HF gallery ventilation system.

The engineering run therefore started on 11. November with a delay of one week. Unfortunately, right at the beginning, a vacuum leak in the IH section of UNILAC and a complex software problem at SIS18 prevented beam operation for about another week.

Subsequently, two patterns, one for the ESR and one for the FRS, ran in parallel during the day-time had priority over the entire period, and so both large-scale facilities could be commissioned with the new FAIR control system.

Since the nights and weekends could not be used for the ESR and FRS as well, due to the high manpower requirements during the day shifts, and in order to use the time effectively, the time was used for machine studies. The open slots were tendered and opened for proposals. This opportunity was also used by GSI experiment groups who requested beam for the preparation of their detectors for the experiments planned for 2020. All proposals were evaluated in the GSI machine meeting, prioritized and scheduled according to their priority.

In this way, 36 of 56 of all proposals could be processed, including all A-Proposals.

Initially, only  $^{40}\text{Ar}^{18+}$  was provided, as this beam is particularly easy to maintain in a stable manner. On December 2<sup>nd</sup>, the switch to  $\text{U}^{5+}$  was made after the necessary RF levels were reached at UNILAC. Due to the strong fluctuation in the beam quality of the  $\text{U}^{5+}$  beam and the relatively low intensity, it was decided in recent weeks, to switch the source to  $\text{U}^{4+}$  and accept the resulting losses caused by the insufficient level of the HSI RFQ. Thus, in the end,  $1 \times 10^9$  particles per spill could be accelerated in SIS18 (Figure 79), which corresponds to the minimum requirements of the planned experiment program for 2020.

However, the ESR commissioning was still carried out with Ar beam, since the stable conditions were initially assessed as more important and, literally, on the last day, December 19<sup>th</sup>, it was possible to transport the decelerated extracted beam to the CRYRING and store it in a stable manner. This was the first time that the complete accelerator chain including the CRYRING was operated completely with beam at GSI.

The engineering run was therefore a great success, even though the test of the complete chain with uranium beam could unfortunately not be carried out. Also not all operating modes could be tested at the ESR (e.g. stochastic cooling). These will probably extend the setting times for the storage ring experiments in the beam time 2020 a little bit.

In retrospect, it can be said that the engineering run was absolutely necessary for the coming beam time.

## 14.3.1 UNILAC-recommissioning with uranium beam

Author: W. Barth

After first careful commissioning phase at the RFQ of the high current injector (HSI) with newly installed electrodes (see this report on “HSI RFQ electrode exchange”, M. Vossberg), about 85% of the nominal Rf-voltage could be reached. In a dedicated machine run stable uranium ( $4+$ ) beam acceleration up to 120 keV/u could be confirmed at this reduced voltage. An uranium beam current of 11.5 emA was available from ion source's LEBT; behind the RFQ a particle current of more than 7emA could be achieved, this corresponds to a particle transmission of more than 60%. Since a significant number of uranium particles are not or only partially accelerated at this low voltage level and, above all, the high intensity uranium beam can only be insufficiently matched to the RFQ structure and to the subsequent Superlens and IH-DTL (Integrated H-type Drift Tube Linac), the beam had to be collimated in the HSI for further acceleration up to 1.4 MeV/u, whereby the intensity had to be reduced by almost 50%. The  $U^{4+}$ -RF-voltage level for both HSI-IH-tanks was fully available; for stable beam transport through the MEBT, a slightly reduced Superlens voltage had to be set. Last but not least the entire HSI could be operated at an  $U^{4+}$ -current of  $(4.0 \pm 0.3)$  emA. The HSI-particle transmission under these difficult conditions was acceptable at 55 %.

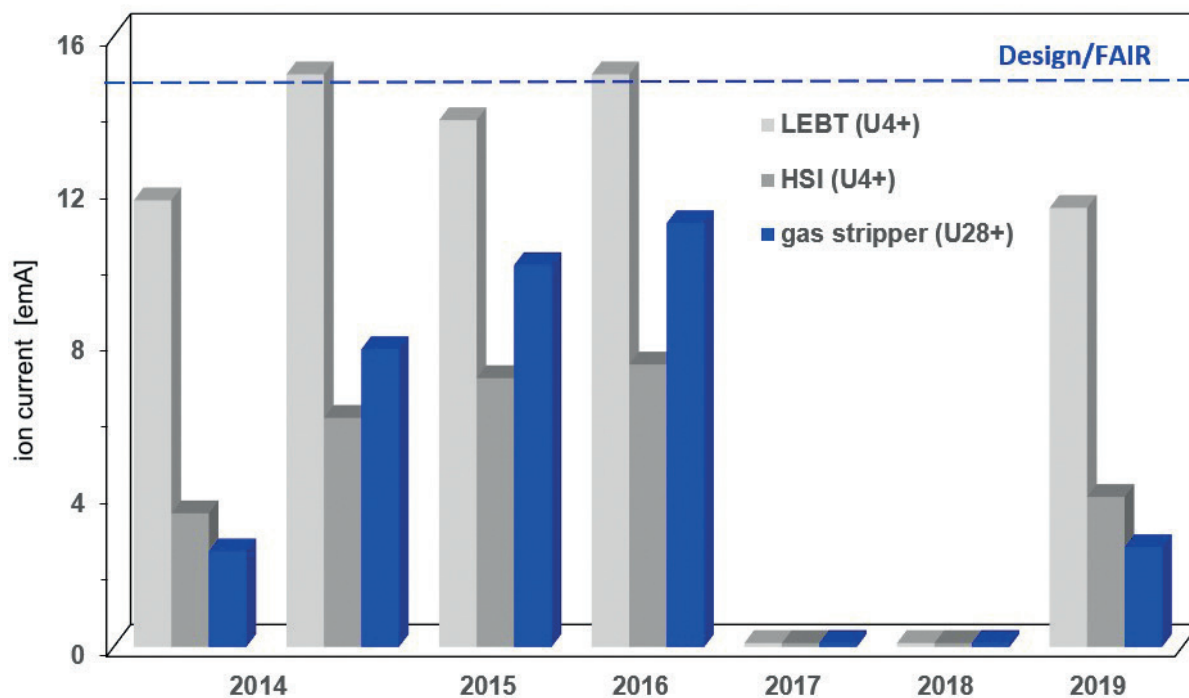


Figure 80. Development of HSI- $U^{4+}$  beam current (2014-2019).

Applying gas stripping with the standard supersonic nitrogen gas jet at 1.4 MeV/u, an  $U^{28+}$  current (at a stripping efficiency of roughly 12%) of 3 emA could be transported through the charge separator system. It is the first time after more than three years [1] that uranium beams can be accelerated at UNILAC. As shown in the Figure 80,  $U^{28+}$  intensities of more than 11 emA were achieved in 2016 through a dedicated machine development program [2]. Now intensities on the level of 2014 can be reached again. The  $U^{4+}$  intensity is essentially limited by the reduced high current performance of the recently installed new LEBT-Quadrupole Quartet, the described reduced RFQ electrode voltage and the unavailability of the pulsed hydrogen stripper. Further on the uranium beam could be accelerated up to 8.6 MeV/u, because tank Alvarez 4 was not available during engineering run 2019. Beam transmission through poststripper and transfer line (53%) was limited due to four missing quadrupoles inside Alvarez tank 1 and tank 3, a reduced quadrupole field strength for the remaining Alvarez quads due to parallel operation with lighter ions and an una-

voidable mismatch to poststripper because of the adapted HSI-RF-setup. Finally, an  $U^{28+}$ -beam intensity at the end of the transfer line (TK7) of  $1.1 \pm 0.1$  emA ( $>1 \times 10^{10}$  particles in a 0.1 ms pulse) could be achieved during an observation period of one hour. The beam has been also stripped to charge state 68+, at a nominal (foil) stripping efficiency of 15% an  $U^{68+}$ -beam intensity of 450 eμA ( $\approx 4 \times 10^9$  particles in a 0.1 ms pulse) was ready for SIS18 injection. Further UNILAC-upgrade measures meeting the FAIR requirements are already proposed.

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## Commissioning of deceleration of ESR

Author: Markus Steck

Recommissioning the ESR after upgrading to the new LSA control system continued in 2019. In a period of 3 weeks in spring, the beam from SIS was available to continue commissioning in the synchrotron mode during ten days. The transfer from SIS to ESR was optimized and first tests of beam deceleration in the ESR were commenced. A deceleration of  $Ag^{45+}$  from 260 to 110 MeV/u with an efficiency of 70 % was achieved. The fact that only the ring magnets could be ramped, but not the magnetic components of the electron cooler limited the energy range. This period was also used for first tune measurements and commissioning of the new data acquisition system of the beam position monitors. Tune and chromaticity measurements allowed an investigation of strategies to improve the ion optical model and the ability to apply chromaticity corrections. The spring period was also used for first operation of the new barrier bucket system, which demonstrated flexible longitudinal compression of the stored beam as required for beam accumulation and beam transfer to CRYRING.

During the shutdown period in the summer, experimental equipment was installed in the ESR required for experiments in the user beam-time 2020. Over the whole year, control system and accelerator experts prepared the operation of the ESR in the storage ring mode.

In the second commissioning period in the four weeks before Christmas, the storage mode for the operation of the ESR was successfully launched and prepared for the planned user operation in 2020. It was successfully demonstrated that this mode allows beam storage for an unlimited time period, different from the synchrotron mode which previously limited the time of beam storage to about 100 s. In the storage mode, beam deceleration was further improved, e.g. it was demonstrated that an  $Ar^{18+}$  beam can be decelerated from 70 to 13 MeV/u with 50 % efficiency. This demonstration also included full control of the electron cooling system in the ramped mode. The investigations on the real ion optical properties of the ESR were also continued and resulted in tune and chromaticity measurements, which will allow further optimization of the ion optical model.

During the second beam time block, also the transfer of SIS beam via the fragment separator FRS was demonstrated in LSA operation. Tests were performed on the accumulation of ions in the ESR by RF-stacking with proper control of ramping the rf -system. At the end of this run, the deceleration to 13 MeV/u was employed in a test of beam transfer from ESR to CRYRING@ESR. Another achievement was the synchronization of the ESR extraction kicker and the CRYRING injection kicker. After two days of beam-line tuning the beam could finally be transferred to CRYRING and stored therein.

## 14.3.2 CRYRING@ESR Commissioning 2019

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

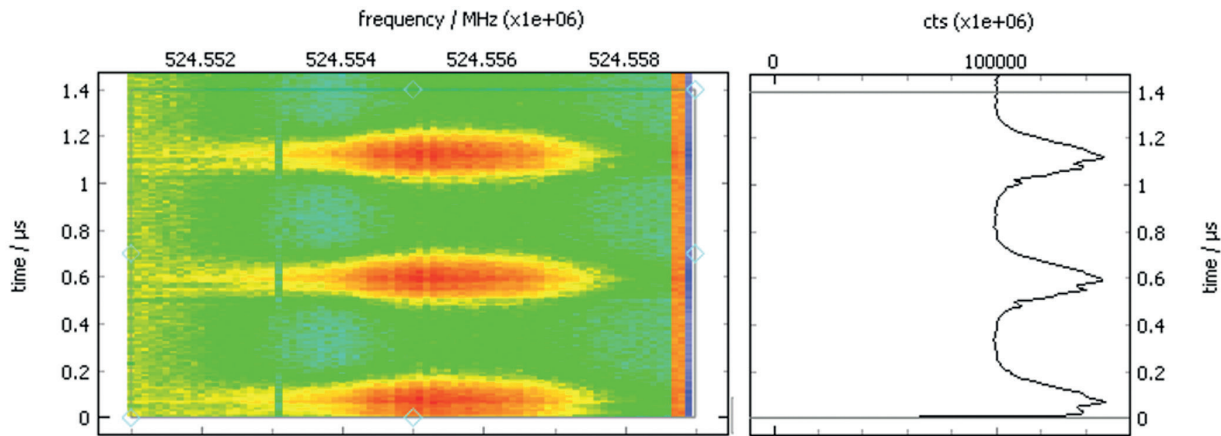


Figure 81. Detection of Mg fluorescence in section YR07. Left: emitted light measured as ion bunch revolution time vs laser frequency. Right: the projection on the time axis.

In 2019, four commissioning runs were scheduled with a duration of three to five weeks. The first run in March through April was foreseen for control system debugging, production of  $\text{Mg}^+$  ions in the local Nielsen-type ion source (MINIS) for a laser spectroscopy experiment, as well as for recommissioning of the CRYRING electron cooler with a modified cryogenic system. After the successful control system restart, up to  $10^7$   $\text{Mg}^+$  ions were injected at 1.5 keV/nucleon, stored and accelerated to the full ring rigidity of 1.4 Tm that corresponds to around 170 keV/nucleon. By the end of March, they were delivered to the experiment, which recorded the first fluorescence signal and proofed the principle operation mode for future measurements. Further investigations were hindered by problems with the electron cooler cryostat. Continuation of the experiment is planned for 2020.

The second beamtime period scheduled in June for the test of the extraction system and beam line had to be cancelled, due to unavailability of the industrial controls resources, required for configuration and tests of the vacuum system. It was later rescheduled for November 2019.

The summer 2019 shutdown period was used for extensive test of the cryogenic system for the CRYRING electron cooler as well as for preparation of the coming experiments. In cooperation with the Gießen University, an electron cyclotron resonance (ECR) ion source was tested and integration into the FAIR-GSI control system was prepared.

The third and fourth beamtime periods took place from end of September to December with a seamless transition into the GSI wide engineering run. After intensive control system debugging in the first week, CRYRING was able to provide up to  $10^7$  singly charged C ions by breaking  $\text{CO}_2$  molecules in the MINIS and transporting them through the linear accelerator to the ring. The ions were then injected into the ring at 3 keV/u, stored and accelerated to 700 keV/u, with a resulting beam lifetime of around 5 seconds. Ion beam scrapers, the overlap with the laser beam and the experiment data acquisition system were tested towards the experiment E129. Eventually the first 10 shifts of  $\text{C}^+$  beam were delivered to this experiment. Additionally, a series of machine studies was conducted, most notably the investigation and correction of the main dipole delay with respect to the RF acceleration voltage.

In the second part of the engineering run the kicker and the extraction beamline were successfully commissioned and CRYRING was prepared for ion injection from the ESR. This comprised a coupling of several accelerators in a single chain, quasi-parallel operation of both injection beamlines and finally, the injection and storage of  $\text{Ar}^{18+}$  ions ejected from the ESR. Due to delays with the setup of beam through the GSI accelerator chain the  $\text{Ar}^{18+}$  beam ejected from the ESR was

available for only 1.5 shifts at the very end of the engineering run. In combination with the large system response latency there was no possibility for detailed investigations. Nevertheless, stable storage of around  $10^6$  ions and a beam lifetime of some 10 minutes were observed. Investigations postponed to 2020 include precise intensity measurements, optimization of storage parameters, injection of heavy, highly charged ions and beam lifetime measurements, as well as preparations for further PAC approved experiments.

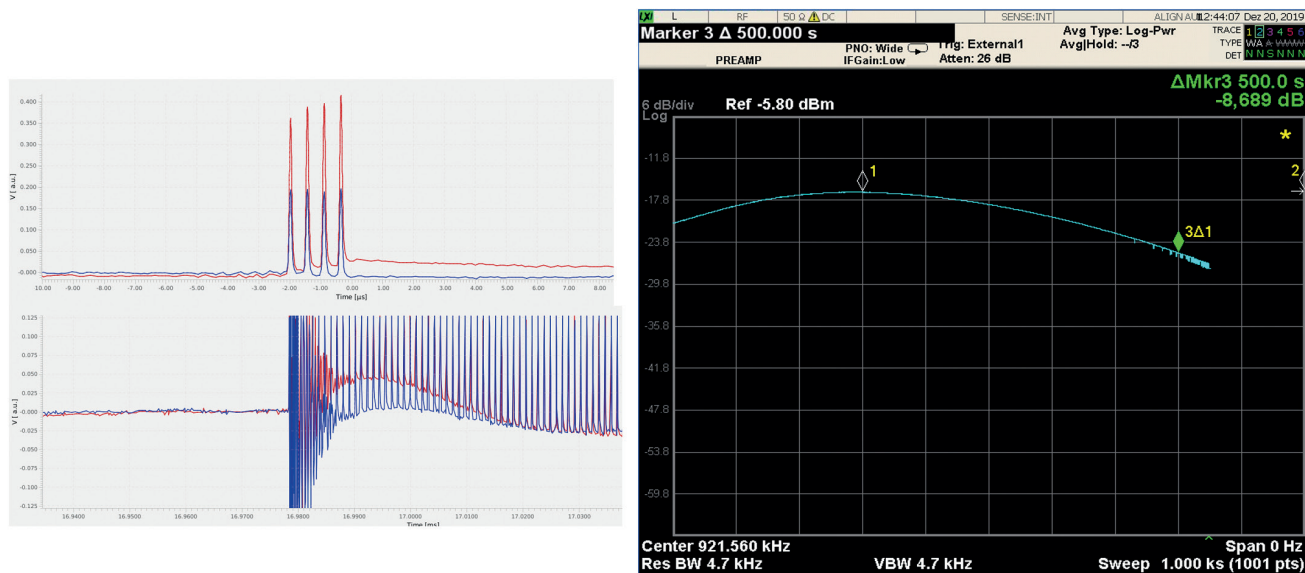


Figure 82. Left: four bunches ejected from the ESR were detected in the YR02 diagnostics, observed on the CRYRING beam position monitors and optimized for multiple turns, as shown on the figure below. Right: Screenshot of the zero span spectrum at the first harmonic of the  $\text{Ar}^{18+}$  beam injected from the ESR and stored in CRYRING@ESR with 13 MeV/nucleon. The initial rise in the signal is attributed to rebunching after injection. The displayed signal drop of around -8.7 dB within 500 seconds corresponds to one beam lifetime.

### 14.3.3 Cooling Progress and Status of the three GSI electron coolers in 2019

Author: R. Hess

In 2019 the activities of the electron cooling group concentrated on i) the commissioning and refinement of the control-system for the operation of the ESR electron cooler in synchrotron and storage-ring mode and ii) the improvement of the liquid Helium filling system of the CRYRING electron cooler gun solenoid. After all the efforts spent on the SIS18 electron cooler in 2018, this cooler is fully operational and has been operated by the regular operating-team throughout the year 2019 without major complications.

#### ESR

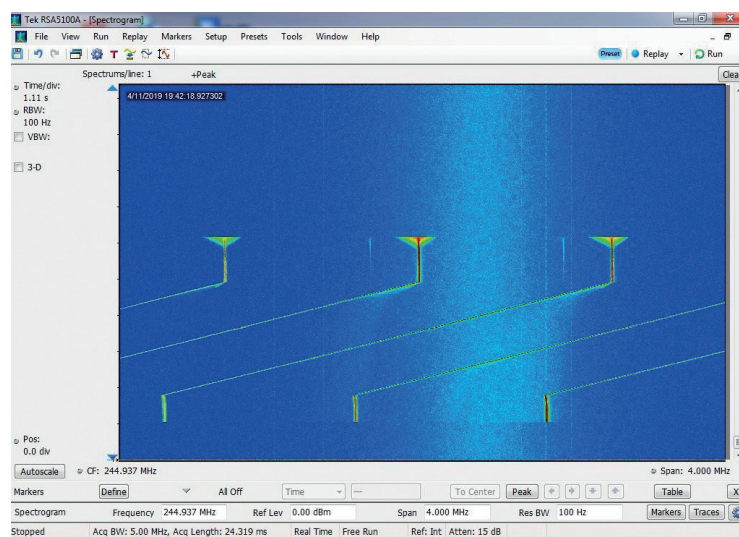


Figure 83. Schottky spectrum showing three harmonics of the revolution frequency. The electron cooler first cools the injected ion-beam and then decelerates it to a lower energy. The acceleration voltage of the cooler is changed by - 2400 V ( i.e. 3.6% of the ion-beam energy;  $\text{Fe}^{25+}$ @120MeV/u) over a time period of 10 s. The electron beam current is 400 mA. On the ramp we see no losses of ion beam particles.

In spring 2019, we managed to run the ESR electron cooler in the so-called ramped-mode. The cooler can be implemented as a particle transfer in a regular ESR pattern and all device values are set via ParamModi and LSA. In close collaboration with the modelling team, properly working modifications of the control-system/ model were developed, in order to prevent unnecessary continuous ramping of all cooler-devices. Now, the cooler magnetic field and the cooler acceleration voltage stay constant, unless a ramp is explicitly implemented into the pattern (see Schottky spectrum in the Figure 83).

Using the “manipulation”-feature of the storage-ring mode, the cooler acceleration voltage can be fine-tuned at a given point in the cycle and used e.g. to shift the ion-beam through the acceptance of the ESR to perform tune measurements.

Summarizing the activities, all cooler device values can be controlled with the new control system in static as well as in ramped mode of operation - allowing flexible parameter control and easy tuning, which was demonstrated during the engineering run.

## CRYRING

The activities at the CRYRING electron cooler mainly focused on the improvement of the liquid helium filling system of the gun solenoid. A new transfer line had been ordered and installed, including a bypass to be able to cool down the transfer line prior to the actual filling procedure. After several iteration cycles a successful filling procedure could be implemented, that allows for an efficient filling of the magnet and cryostat. The liquid helium consumption amounts to 6.8 l / day which corresponds to the experience from Sweden. On the hardware side, we refurbished the power supply of the superconducting gun solenoid and installed a fast high voltage switch for the electron extraction anode. This enables a fast and remote control of the electron-beam, as it is already available at the ESR and SIS18 cooler.

## 14.3.4 Beam Instrumentation activities

Authors: P. Boutachkov, H. Bräuning, O. Chorniy, P. Forck, R. Haseitl, T. Hoffmann, W. Kaufmann, P. Kowina, K. Lang, T. Milosic, S. Mirza, H. J. Reeg, A. Reiter, M. Saifulin, M. Schwickert, R. Singh, B. Walasek-Höhne, all GSI

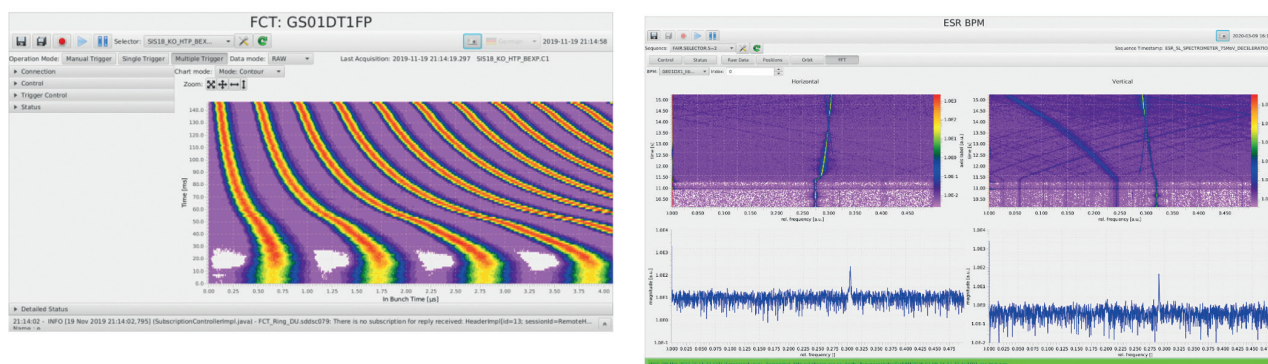


Figure 84. Examples for new DAQ systems: Left: Contour plot of bunches accelerated in SIS18 recorded by the FCT. Right: Horizontal and vertical tune measurements (tune spectrogram and spectrum) during deceleration in ESR.

As part of the engineering run in autumn 2019 important developments of the GSI Beam Instrumentation Department were tested and verified. This report highlights developments on novel readout software, closed-orbit feedback tests and investigations on novel scintillator materials.

A remarkable number of FESA classes and graphical user interfaces (GUI) were developed for various beam instruments and are now used in standard operation by the accelerator operators. Moreover, these hard- and software realizations act as a testbed and precursor for FAIR beam diagnostics. Here recent installations for two instruments are exemplary discussed.

The signal from the fast current transformers (FCT) at SIS18 and ESR are digitized by modern 2.5 GSa/s, 14-bit resolution ADC modules using the  $\mu$ TCA standard. The FESA class on the front-end controller (FEC) processes the massive data stream recorded during the entire synchrotron cycle. As depicted in Figure 84 (left), a performant client application provides enhanced online features such as trending plots of bunch profiles within the SIS18 cycle with, e.g. a user-friendly zoom function for regions of interest.

Readout of the beam position monitors (BPM) is performed by Libera Hadron units at a raw sampling rate of 250 MSa/s. Position data are evaluated leveraging the integrated FPGA up to a bunch-by-bunch basis. These data are transferred to the client either at a fixed rate or, depending on configuration, once after the full cycle. Two frequently used applications are closed orbit determination and transverse tune spectra. Exemplary, Figure 84 (right) depicts a tune measurement at ESR during ramping (deceleration of a Xe beam from 75 to 15 MeV/u).

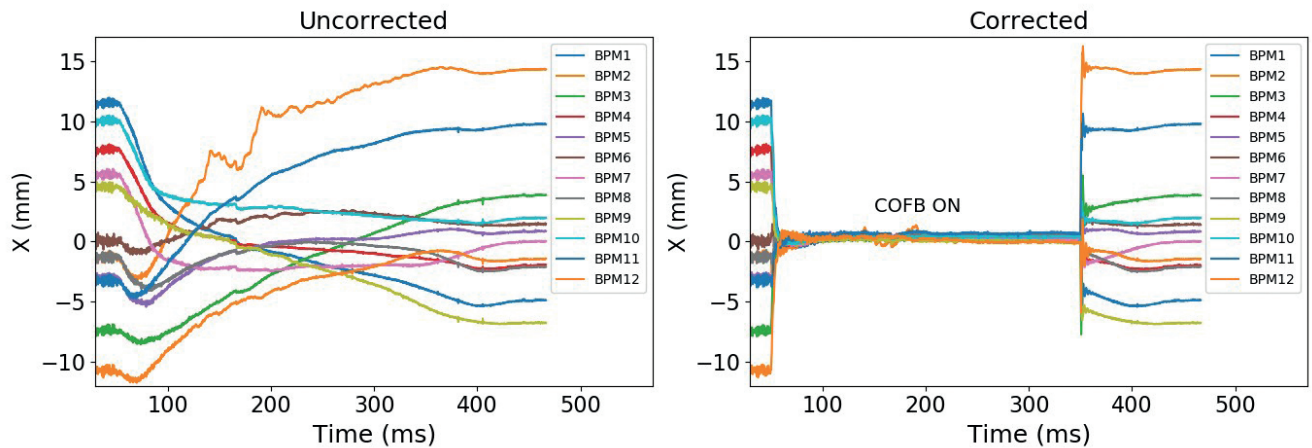


Figure 85. The perturbed (left) and corrected orbit (right) for a finite duration within the acceleration of an  $\text{Ar}^{18+}$  beam from 11.4 to 300 MeV/u.

A fast closed orbit feedback (COFB) system was implemented at SIS18 synchrotron in the horizontal plane [1]. The system is capable of disturbance rejection up to 300 Hz and is the first of its kind in terms of on-ramp orbit correction and robustness against model mismatch from injection to extraction [2]. Figure 85 shows an example of the perturbed orbit (left) recorded on all 12 BPMs and the corrected orbit (right) where the COFB system was set active for a finite time within an acceleration cycle. The achieved variations of the closed orbit are below  $\Delta x_{\text{rms}} < 1$  mm, i.e. much smaller than 10 % of the typical beam size and better than the acceptance criterion of a typical COFB system.

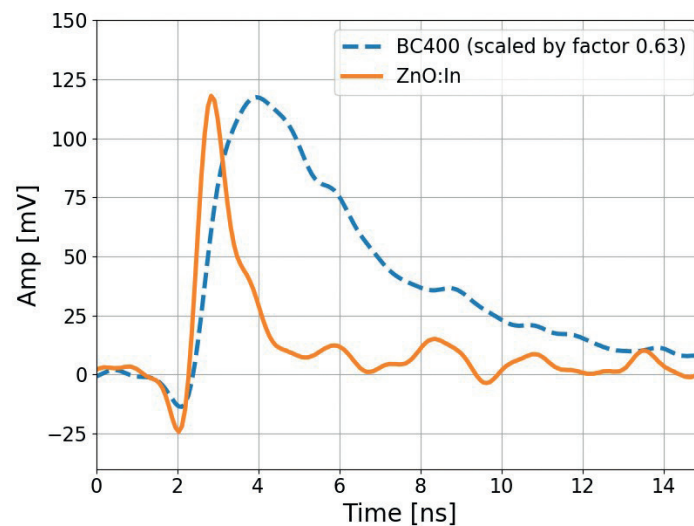


Figure 86. Comparison of the rise and fall times of ZnO:In and BC400 scintillators recorded by Hamamatsu H13661 photo-sensor module for a 300 MeV/u  $^{238}\text{U}$  beam.

At GSI high-energy beam transport lines (HEST), BC400 organic scintillators are regularly used for absolute beam current and micro-spill structure measurements [3]. Due to the low radiation hardness of this material, alternative inorganic scintillators like ZnO:Ga and ZnO:In are investigated [3]. The radiation hardness and time properties of these materials are superior compared to plastic scintillators. The response to 300 MeV/u  $^{238}\text{U}$  ions of 0.4 mm thick ZnO:In ceramics is depicted in Figure 86 and compared to 1 mm thick BC400 plastic scintillator. It shows that the rise and decay times of ZnO:In are significantly shorter than for BC400.

The initial studies [4] proved that ZnO is at least a factor of 100 more radiation hard compared to BC400. Various samples were investigated, providing information on best manufacturing techniques for serial production. It was verified that the damage from heavy ion bombardment can be repaired by annealing. Further offline characterization by materials science methods of the irradiated ZnO samples is ongoing.

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## 14.4 General research & developments for accelerators

### 14.4.1 18GHz ECRIS upgrade

Authors: K. Tinschert, F. Maimone, R. Lang, J. Maeder, P. Patchakui

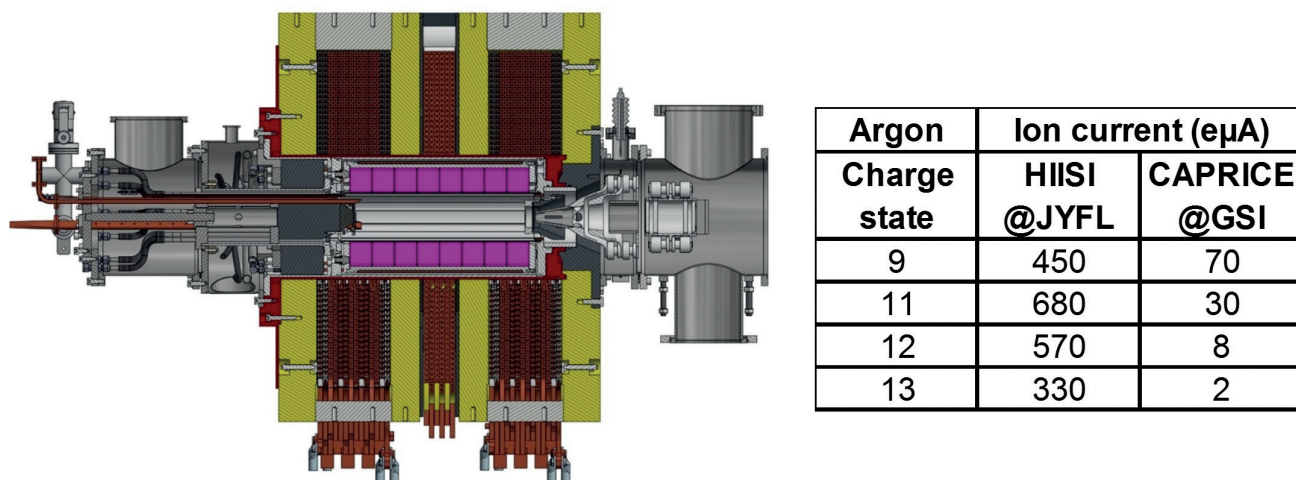


Figure 87. (left) Sectional view of HIISI; length of source body (yellow green): 750 mm; solenoid coils (dark red); permanent magnet hexapole (magenta) (courtesy: University of Jyväskylä); (right) comparison of intensities (HIISI versus CAPRICE) for various Ar charge states.

At the High Charge State Injector (HLI) of GSI the CAPRICE ECR ion source (ECRIS) is in operation since 1992. Its technical standard is outdated and implies the replacement by adequate technologies.

In order to obtain higher ion beam intensities from an ECRIS source an increase of the plasma density is required. This implies higher microwave frequency which in turn demands the increase of the confining magnetic fields according to the ECR condition. So, it was decided to implement first a conventional ECRIS working at 18 GHz as upgrade while later the development of a superconducting ECRIS operating beyond 22 GHz is planned.

At the JYFL Accelerator Laboratory a high performance ECR ion source (Heavy Ion Source Injector, HIISI, Figure 87, left) has been built which applies innovative technical solutions and which achieved excellent results in terms of attainable ion beam currents (Figure 87, right). Hence the decision was taken to implement a copy of this ECRIS at GSI. In order to establish an optimal procedure a cooperation agreement has been accomplished between the University of Jyväskylä and GSI, which defines transfer of know-how and joint R&D on the investigation and future development of this type of ECRIS.

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## 14.4.2 High current ion source development for FAIR

Authors: A. Adonin, R. Hollinger

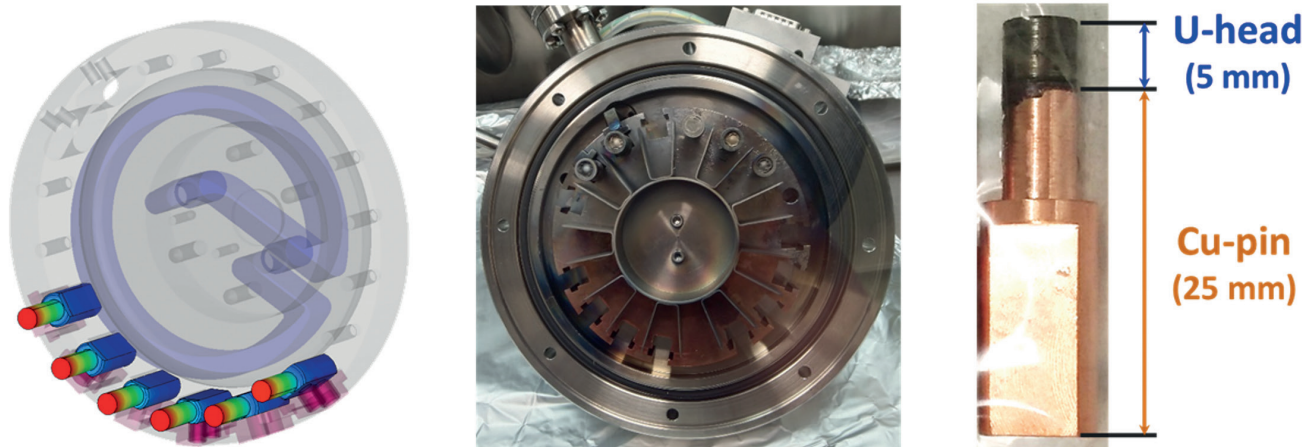


Figure 88. New water-cooled cathode revolver for VARIS: simulation of the heat-transfer from the working surface to the flange (left); prototype used in performance tests (middle); U-Cu cathode of a new geometry (right).

One of the key-elements for the experimental program at the future FAIR facility is uranium. At the end of FAIR Phase-0 the operation of intense uranium beams will be required at a repetition rate of 2.7 Hz [1]. At present the production of intense  $U^{4+}$  beams from the VARIS ion source [2] with a repetition rate of 1 Hz is well established, using metal electrodes of depleted uranium. Therefore, part of the development program of high current ion sources is dedicated to increase the repetition rate of  $U^{4+}$ -ion production without notable reduction of the ion source performance and of the beam quality.

Operation of the ion source with increased (almost by a factor of three) repetition rate leads to notably higher thermal load on the U-cathode surface. This often results in ignition failures of the vacuum arc (no ion beam production during such pulses) and in pulse-to-pulse instabilities. As a possible solution, the use of a U-W composition instead of pure U in the cathodes has been tested [3]. It was shown that the concept of composite materials generally works, allowing 2.7 Hz U-operation. However, the manufacturing process of the cathodes is rather complicated and the desired uniformity of the material quality could not be achieved. Another critical aspect was the occurrence of instability phases (5 to 30 min duration) during the cathode operation, which covered up to 25% of operation lifetime of the cathode [3]. Due to these two issues the concept of composite cathodes for establishing stable  $U^{4+}$  operation with 2.7 Hz has to be discarded.

Another possible solution is the implementation of an active cooling system for the cathodes. A new cathode revolver with water-cooling channel inside and an enhanced cathode holder geometry has been designed (Figure 88, left). It requires a modified geometry for uranium cathodes: the U-head (cylinder of  $\varnothing 6$  mm and 5 mm height) is soldered on a Cu-pin. Its shape is optimized for maximum heat transfer from the working surface of uranium to the cooled flange (Figure 88, right).

A prototype of such a water-cooled revolver has been manufactured (Figure 88, middle). It is capable to accept mounting of both cathode versions: the new one (with improved heat conduction) and the old one for standard U-cathodes. A particular difficulty is the production of U-Cu electrodes. In order to achieve a proper thermal conduction between U-head and Cu-pin, various methods have been considered: conventional soldering using various solders, ultrasonic soldering, spot welding and electro-magnetic pulse technology (EMPT). The first set of U-Cu electrodes using conventional soldering and spot welding have been prepared for the tests.

The first tests of the VARIS equipped with water-cooled revolver and U-Cu cathodes have been performed at terminal North in Jan.-Feb. 2020. Six cathodes were tested (including the standard U-cathode for comparison) in the following operation mode: 2.78 Hz / 0.45 ms (pulse length). The average lifetime of one cathode was about six hours. All cathodes showed very fast conditioning. After 10 minutes of operation they could provide 80% of the maximum current. Various U-Cu cathodes have shown slightly different performance for  $U^{4+}$ . However, all of them showed "instability phases" during operation. These phases appeared randomly lasting between 5 and 40 minutes. During these phases the ion source performance dropped drastically, and it was not possible to recover it by variation of the ion source parameters. Figure 89 shows the stability for two hours of U-Cu cathode operation with stable operation phases of excellent performance and with phases of instability and drastically lower performance.

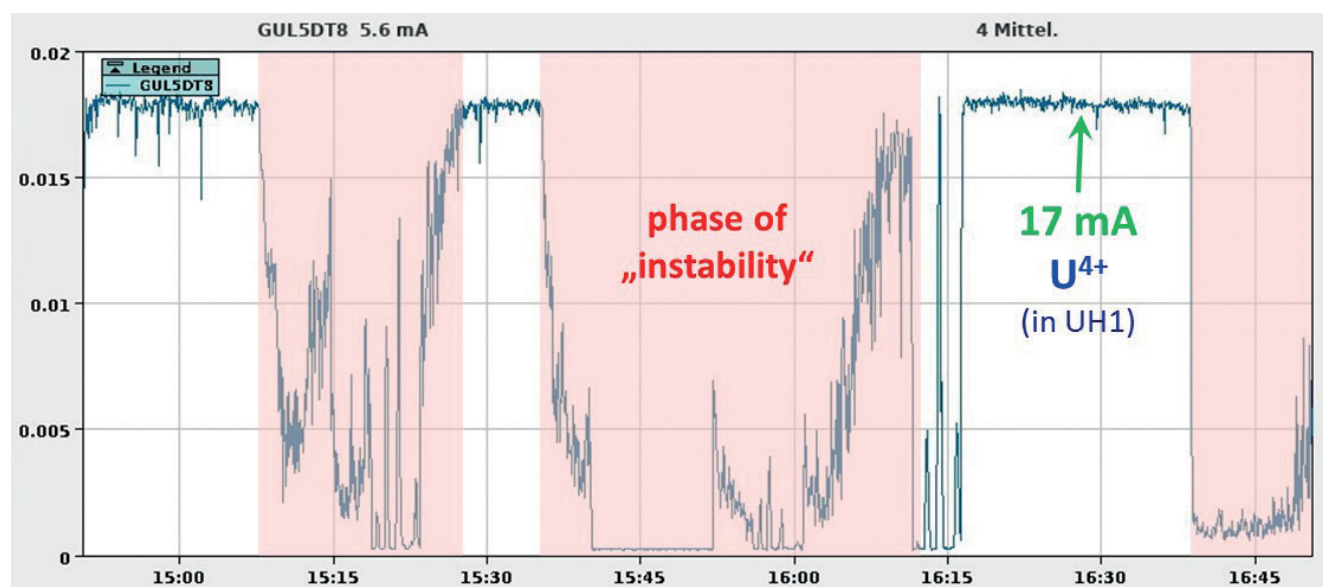


Figure 89. Operation stability over two hours with 2.78 Hz repetition rate. Current-time plot for  $U^{4+}$  beam from the current transformer GUL5DT8.

The origin of the instability phases is not yet identified. It could be connected with the material quality of uranium as well as with the manufacturing process (soldering/welding) of the U-Cu cathodes. Hence, the stable high current operation of  $U^{4+}$  ion beams with 2.7 Hz repetition rate could not be established yet. Further investigations and tests are needed.

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## 14.4.3 Optical spectroscopy for metal ion beam production with ECRIS

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

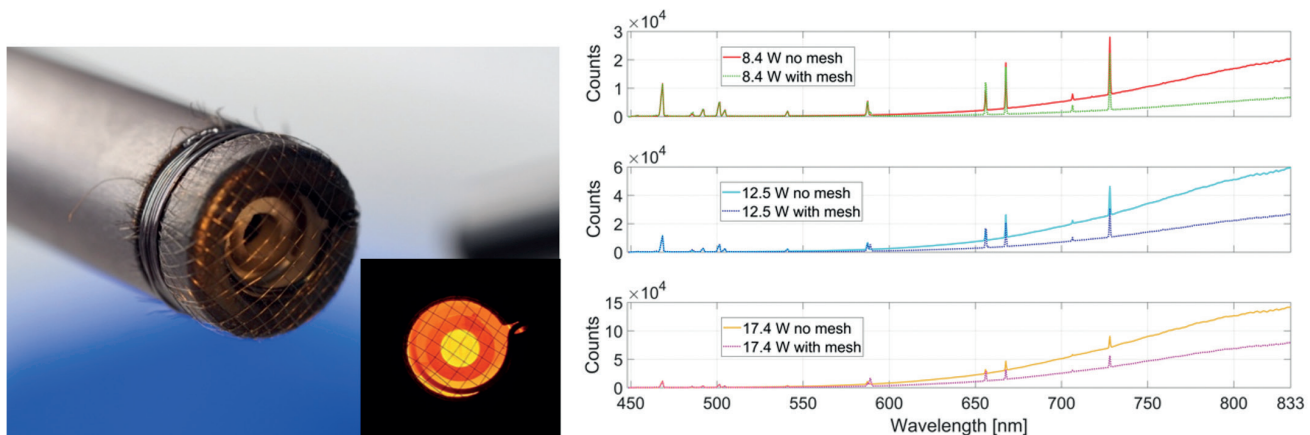


Figure 90. (Left) Microwave shielding mesh at the front part of the oven and a sample picture of the shielded hot oven. (Right) OES measurement with and without mesh at 650 W microwave power for three oven powers.

At GSI the CAPRICE ECR Ion Source (ECRIS) is used to provide heavy ion beams for the UNILAC. In order to satisfy the demand of metal ion beams a resistively heated oven is routinely used. This evaporation technique allows the ion beam production from natural and enriched solid elements or compounds with high efficiency and low material consumption. Often it is required to provide high charge state ion beams from rare or extremely rare isotopes as  $^{48}\text{Ca}$ , in particular for the investigation of super heavy elements. In order to maintain the ion beam for the entire beam time, the plasma inside the ion source must remain as stable as possible. The tuning of ion source parameters and oven power affecting the oven temperature and in turn the evaporation rate is necessary. A strong relationship was observed between the microwave power and the oven heating, thus affecting the power control, the plasma stability and the material consumption. In particular for the operation of  $^{48}\text{Ca}$  sometimes it is difficult to find a working point to guarantee a long-term stable equilibrium as the oven setting and the response time of the ECRIS are relatively slow.

Optical emission spectroscopy was implemented by analyzing the light from the plasma and from the oven through the extraction aperture. It was investigated how the continuous monitoring by an optical spectrometer facilitates fast detection of plasma instabilities.

It has been also demonstrated how the measured optical spectrum can be used to detect the parasitic heating of the oven by microwave. A tungsten mesh has been used to shield the oven orifice and a remarkable reduction of the parasitic heating has been measured with an optical spectrometer achieving up to 69% shielding, as shown in Figure 90.

This result is promising for optimized ECRIS operation with metal elements like  $^{48}\text{Ca}$ .

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### 14.4.4 Follow up of the optimization of SIS18 extraction spill

Authors: R. Singh, A. Bauer, P. Forck, H. Huether, P. Kainberger, H. Liebermann, D. Ondreka, W. Orlov, H. Reeg, A. Stafiniak, H. Welker

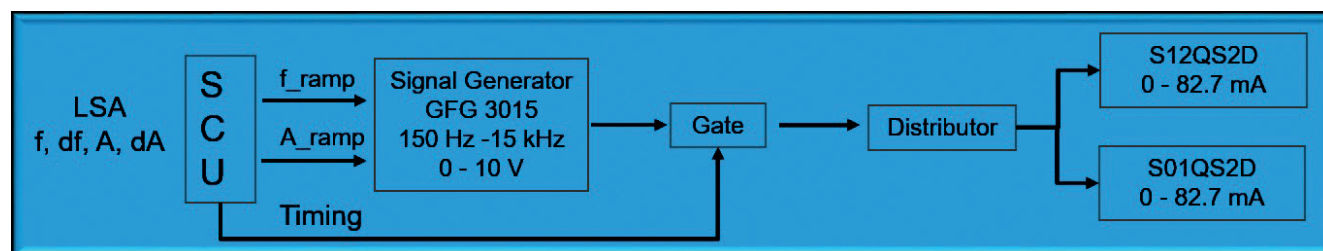


Figure 91. Schematic of the transit time dependent tune modulation system.

A new technique for slow extraction spill smoothing was tested and made available for the HADES beam time in March 2019 [1]. This technique is referred to as “Transit time dependent tune modulation” [2]. In this method, quadrupole currents are modulated with an amplitude corresponding to  $\sim 10^{-4}$  of the nominal current (20-100 mA) in the frequency range of 1-15 kHz. The choice of both the amplitude and frequency depends on the transit time distribution, which in turn is given by the SIS-18 slow extraction settings. During the March 2019 HADES beam time, this signal was coupled via the DCCT in an expert set-up. A summary of new efforts undertaken to make the technique available as a standard tool operable from SIS18-control system are discussed below; further technical details can also be found in [3].

Figure 91 shows the schematic of the transit time dependent tune modulation system. The main element of this system is a GFG 3015 signal generator, which is capable of modulating the amplitude and sweeping the frequency of its output as a function of two independent input signals. The gated generator output avoids interference with other segments of the acceleration cycle. This gated output is fed to the defocusing quadrupole families at their “PE correction input”. The start frequency ( $f$ ) and the range ( $df$ ) as well as corresponding amplitude inputs ( $A$  and  $dA$ ) are specified in LSA which generates a frequency and amplitude ramp from the start through the end of slow extraction period. An SCU card transfers these waveforms to the modulation inputs of the GFG 3015. The limit on the voltage output of the PE corrector defines the maximum correction current  $\sim 100$  mA. A signal attenuator is placed at the input of PE corrector input such that the maximum output of GFG 3015 (i.e. 10 V) corresponds to an output current of 82.7 mA.

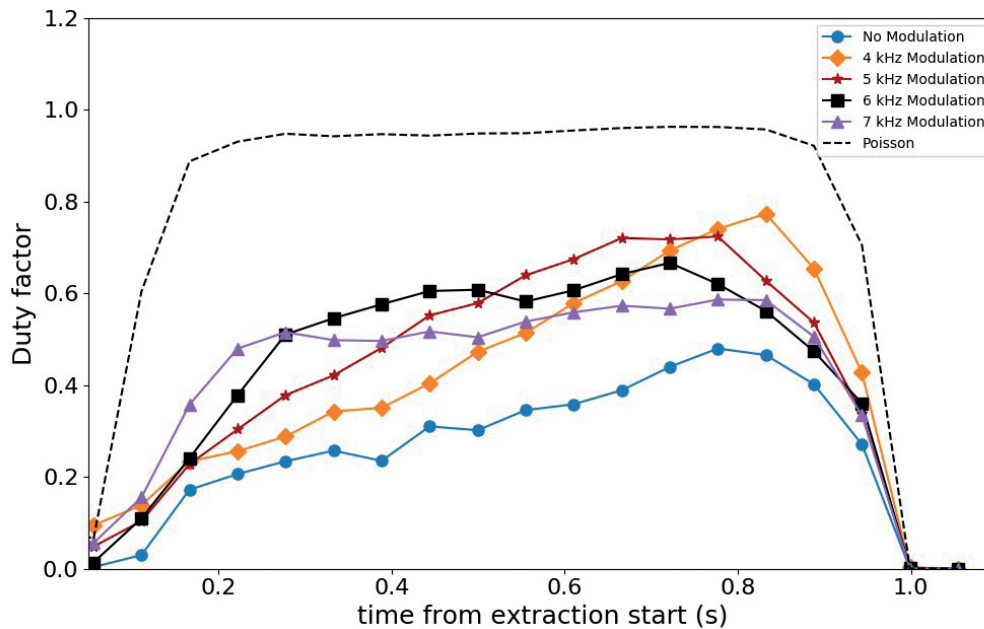


Figure 92. Duty factors of quadrupole driven slow extraction of Ar<sup>18+</sup> beams at E = 300 MeV/u for various fixed frequency tune modulations.

As explained in [2], the transit time distribution varies during the quadrupole driven slow extraction from smaller to larger values, and correspondingly the optimal modulation frequencies change from higher frequencies to smaller from start to the end of slow extraction process. Although the optimal modulation frequencies can be readily found from the corresponding spill spectrum; here we outline an empirical procedure for setting the system-up quickly. In this scheme, fixed frequency current ripples are coupled into the quadrupoles at various frequencies in subsequent spills. This is shown in Figure 92, where duty factors [4] of many quadrupole driven slow extraction spills of Ar<sup>18+</sup> beams at E = 300 MeV/u are plotted for a specific slow extraction set-up while the tune modulation frequency is varied. The amplitude of the modulation current is fixed at 82.7 mA and the modulation frequency is varied between 2 kHz to 9 kHz in steps of 1 kHz. Duty factor is calculated every 50 ms in the spill. For lower modulation frequencies (e.g. 4 kHz), the spill quality is improved towards the end of the spill while higher frequencies (e.g. 7 kHz), spill quality improves at the beginning to the spill. This suggests that the optimal frequency ramp in this case would be between 7 kHz to 3 kHz from start until end of extraction. For now, the maximum available correction current provides the best results for micro-spill quality although the simulations suggest that modulation current amplitude will also have an optimum [2]. Further efforts to couple the current modulation to focusing magnet families to increase the tune amplitude modulation are foreseen. The type of frequency ramps are also under investigation.

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## 14.4.5 Commissioning of ROBOMAT and development of FOUROSE

M. Maier, M. Bauer, A. Bechthold (NTG Neue Technologien GmbH & Co. KG, Gelnhausen, Germany), X. Du, T. Engert, L. Groening, J. Maus (NTG Neue Technologien GmbH & Co. KG, Gelnhausen, Germany), C. Xiao

The detector system ROSE [1], [2], allowing to perform full four dimensional (4d) emittance measurements of 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 4d emittance, has been granted a patent in 2017 [1]. The inventors together with the technology transfer department of GSI have found an industrial partner in order to modify ROSE into a standalone, commercially available emittance scanner system. This is a three-step process involving the hardware, the electronics and the software working packages. It is planned to have a configurable customer product ready by end of 2020. This contribution presents the successful commissioning of ROBOMAT [3] and the actual status of the 4d software package FOUROSE [4].

### Commissioning ROBOMAT at HIT

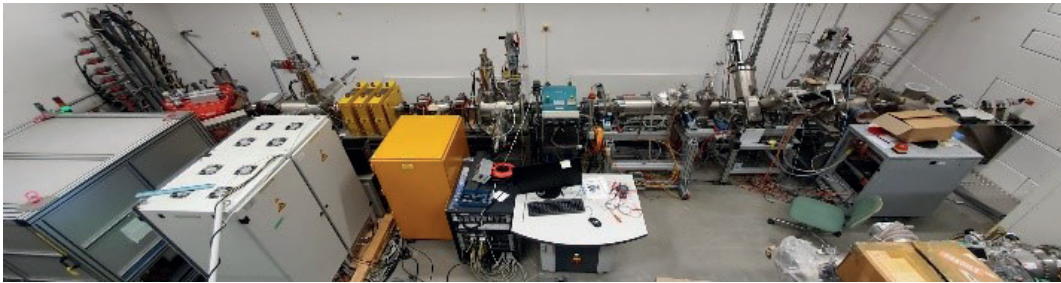


Figure 93. Setup of ROSE and ROBOMAT at the HIT test bench comprising an ECR ion source, 90° bending magnet a magnetic triplet and a solenoid behind which ROSE and the SAG emittance scanner where set up.

After successful factory-acceptance-test FAT at NTG in April, the complete system was delivered to HIT in May 2019. As shown in Figure 92, ROSE was setup in the test beam line of HIT together with another emittance scanner of SAG.

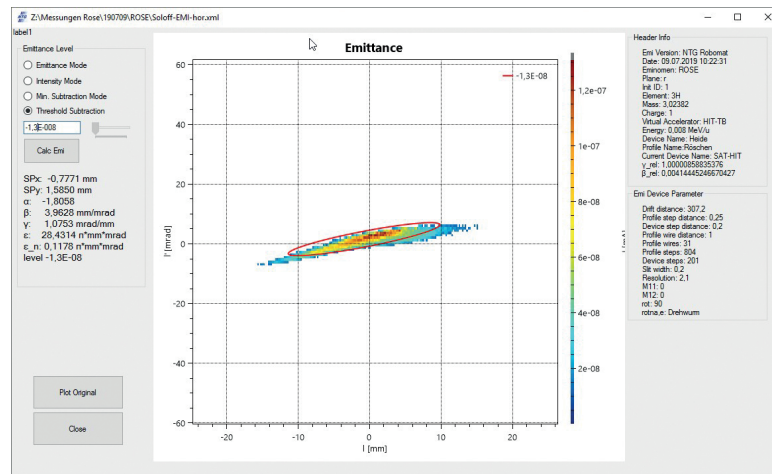


Figure 94. Evaluated emittance scan at 45° of a H3+ ECR beam using the ROSE detector with the ROBOMAT electronics, measurement and data evaluation software.

Figure 94 shows the evaluated emittance data of a H3+ beam using ROBOMAT and ROSE at an angle of 45°.

A comparison of the results obtained using the two different emittance scanners in Figure 95 shows reasonable agreement:

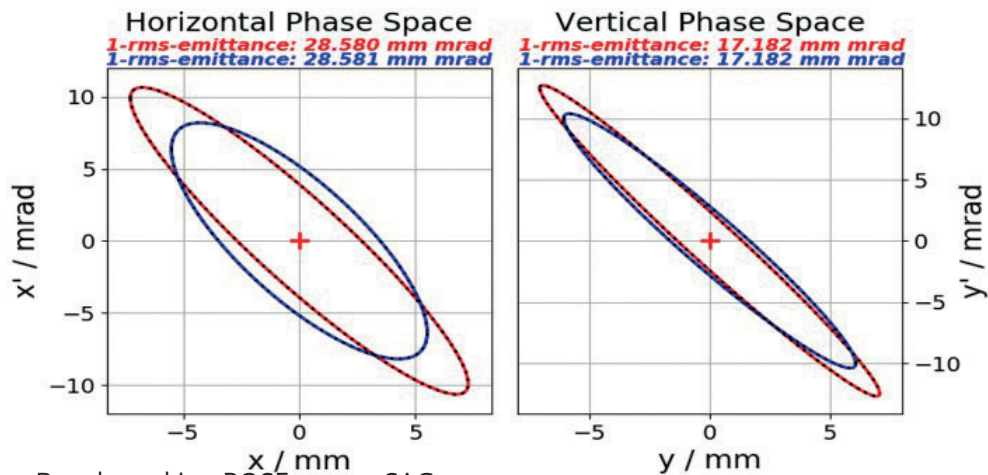


Figure 95. Benchmarking ROSE versus SAG.

## Development of Software FOUROSE

Controlling the drivers of ROSE's actuators, data acquisition and data evaluation were merged into one single software FOUROSE. The first two issues have been tested at HIT and data evaluation of real 4d measurements has been benchmarked by taking data from previous measurement campaigns performed at GSI in 2016 [1]. Beyond the merging, the data evaluation procedure has been further developed and improved. A new method has been worked to significantly improve the accuracy of the finally measured eigen-emittances. The method is based on the novel approach of exploiting the inaccuracy of measured raw data that enter into the determination of the final result. The raw data are trimmed within the window of intrinsic inaccuracy such that the final result (derived from the trimmed data) is fully consistent, i.e., it is not a best fit to all measured data but is consistent to all measured data. The method uses the fact that the measured data are partially dependent from each other. An according manuscript has been submitted to a peer review journal [5].

## Conclusion

We have invented, built and successfully commissioned ROSE, a 4d emittance scanner for heavy ion beams independent of their kinetic energy, intensity and time structure. Together with an industrial partner, we have developed and commissioned the electronics ROBOMAT as a standalone, mobile emittance scanner. The final part of this project has started 2019 and we expect to have the 4d application FOUROSE, as part of a configurable, mobile emittance scanner, ready by the end of 2020 to finally commission the complete system with beam in spring 2021. In parallel the data evaluation has been further improved by developing a novel tool to increase the final measurements results accuracy.

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## 14.5 Accelerator upgrade

### 14.5.1 Progress on the Alvarez 2.0 DTL post-stripper section of the UNILAC

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

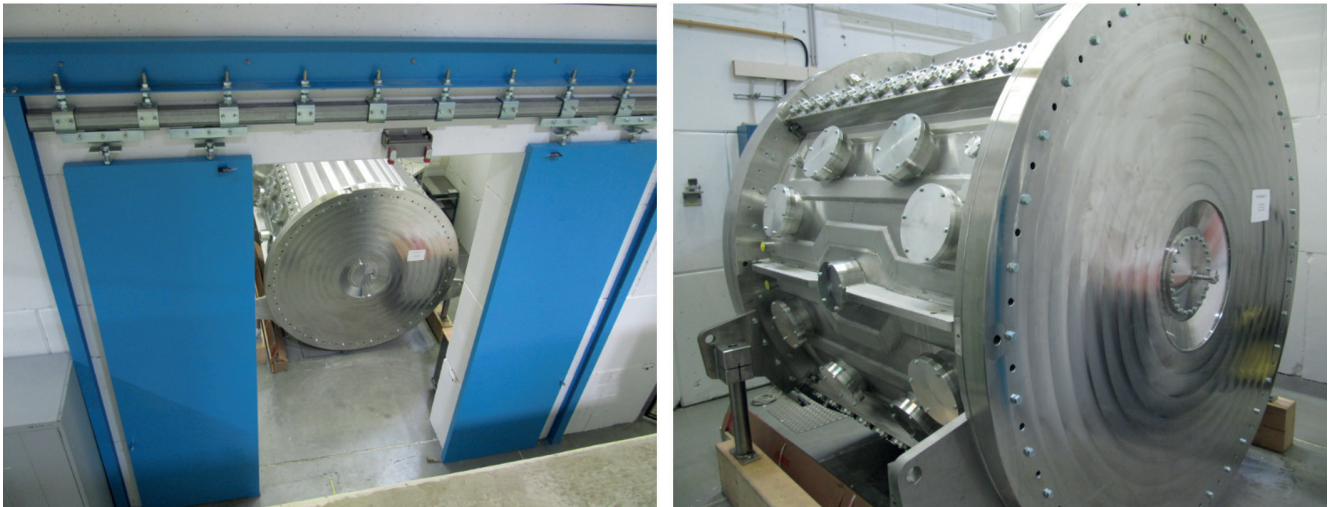


Figure 96. Alvarez 2.0 FoS cavity at the former experimental station Z7.

The realisation of the first cavity section of the new post-stripper drift tube LINAC (DTL), the Alvarez 2.0 FoS (First of Series) project, is in progress [1,2]. The main parts, the tank section, two end-plates, and eleven drift tubes without quadrupoles were delivered in 2019 and successfully accepted on site.

The Alvarez-type cavity was assembled at the former experimental station Z7 in the GSI experimental hall (EH) (Figure 96). Z7 was adapted structurally to meet the requirements for a high-power radio frequency (RF) test stand. A radiation protection bunker was built. An 80 meters long 6 1/8" RF supply line from the UNILAC RF gallery to the test stand was defined. The order for installation of the delivered RF supply line components in Q1/2020 was placed to an external partner (Mastbau FN GmbH). Further infrastructural measures are planned, depending on the test campaign.

The FoS test campaign aims at the qualification of the Alvarez 2.0 DTL design for series production. It is staged to test runs before and after Cu-plating of the components as well as to test runs with and without internal quadrupole lenses inside each drift tube.

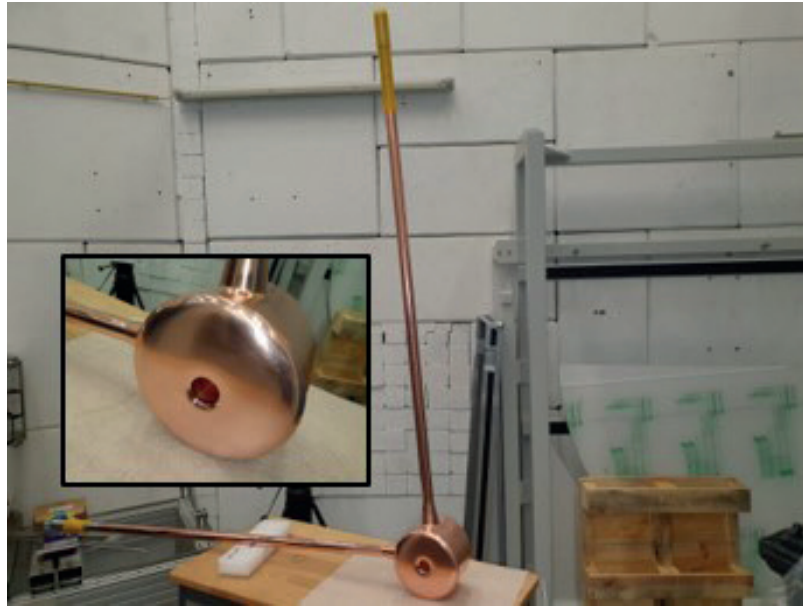


Figure 97. Drift tube and stem after Cu-plating by an external partner.

Before the large FoS components like the tank section and endplates are Cu-plated, a test run with a 1:1 scaled model (dummy) of the FoS tank section has to be completed. The preparations to Cu-plate the dummy have been started. Its completion is expected in Q2/2020. For Cu-plating of smaller components like drift tubes and flanges an external galvanic workshop is considered. Galvano-T electroforming-plating GmbH successfully coppered a complete drift tube & stem set-up within the GSI quality criteria (Figure 97).

The Alvarez 2.0 DTL comprises about 200 drift tubes each with an internal magnetic quadrupole lens for beam focusing. The high number of drift tubes demands industrial production. In view of this fact a study was tendered aiming at a first industrially produced Alvarez 2.0 drift tube delivered in 2020. Danfysik A/S received the order and in December 2019 the CDR was accepted. The procurement of an adequate magnetic power supply has been prepared in parallel.

At the test stand the low-level RF measurements (LLRF) with the un-coppered components have started. The operating frequency was measured and compared to simulations for different configurations, e.g. cavity vented and pumped, equipped with movable tuners and w/o tuners, etc. As an example, two results are highlighted:

- The first measurement was performed with the empty FoS cavity, i.e. w/o drift tubes at atmosphere, all ports were closed with flanges. Measured frequency (117.207 MHz) and simulated frequency (117.203 MHz) agree within few kHz.
- One of the latest measurements was performed at atmosphere with pre-aligned drift tubes and seven moveable tuners at their centre positions. The measured frequency was matched to the nominal frequency at operation conditions of 108.408 MHz by moving in one of the seven tuners moderately.

Positive feedbacks on the progress of the FoS project were received from MAC 21 and MAC 22. Additionally, in November 2019 the Alvarez 2.0 DTL project was reviewed internally. The project roadmap, which ends up with the substitution of the existing Alvarez DTL not before 2028, was confirmed. As critical paths the Cu-plating of the accelerator components and the provision of storage, preparation, assembling, and testing areas from 2022 on were identified.

## 14.5.2 Pulsed Gas Stripper development

Authors: P. Gerhard, M. Maier

### Introduction

The GSI UNILAC together with SIS18 will serve as a high current, heavy ion injector for the future FAIR. These ions will be provided by the high current injector HSI. A stripper, situated at the end of the HSI, is necessary to increase the (very) low charge states of the heavy ions produced by the high current sources in order to enable further acceleration in the poststripper DTL. The stripping process results in an ion beam consisting of a spectrum of different charge states, out of which only one can be used and has to be separated by charge state analysis. The present stripper facilitates a continuous nitrogen gas jet as stripping target. Due to the width of the resulting spectrum, approximately 85% of the beam are not suited for further acceleration. In addition, the increase of the mean charge state is somewhat limited by the current stripper setup.

A modified gas stripper setup has been developed and tested, aiming at an increased yield into the particular desired charge state. It delivers short pulses of high gas density synchronised with the beam pulse. This reduces the gas load for the differential pumping system and allows the use of gases such as hydrogen H<sub>2</sub> and helium He. With H<sub>2</sub> the stripping efficiency for <sup>238</sup>U into the desired charge state 28+ was significantly increased by a reduction of the spectral width as well as an increase of the mean charge state. The latter increase is also advantageous for intermediate mass ions required for experiments close to Coulomb's barrier as it reduces the amount of rf-power needed in the poststripper DTL. However, for heavy ions provided for FAIR this will increase space charge forces and lower the space charge limit inside the SIS18. After the successful proof of principle [1, 2], activities were started to turn the development setup into a system suitable for regular operation.

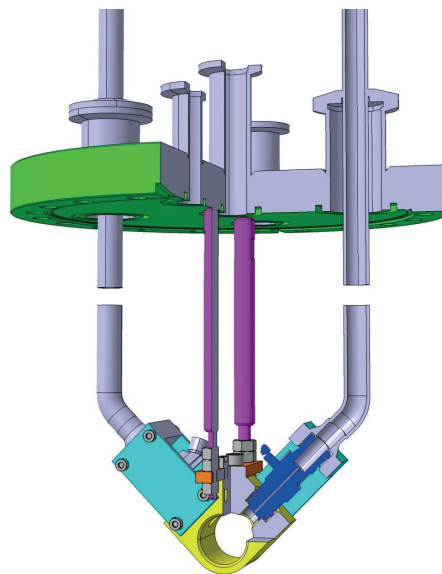


Figure 98. Schematic drawing of the new gas stripper setup. The new pulsed valve is depicted in blue.

## Prerequisites

During an extended test in 2016 problems with the fast valves arose while they were used for a longer period for the first time. It became clear that regular operation could not be achieved with this type of fluid media valves. Another show-stopper was revealed in the vacuum exhaust. For safety and radiation protection reasons, exhaust air from the accelerator vacuum system containing a significant amount of H<sub>2</sub> cannot be disposed of via the vacuum exhaust ventilation system regularly. It was found that there might be no solution to this by an upgrade of the ventilation system due to a lack of appropriate particle filters.

This triggered another revision of the setup and a search for a solution to the exhaust problem. The short service life of the valves could be solved by using another valve type designed for gaseous media. This required a mechanical redesign of the gas stripper [3]. The new design is shown in Figure 98. This setup was tested successfully with Ar beam end of 2018 using H<sub>2</sub> and N<sub>2</sub> as stripper target gases, which qualified the new valve type for application in the UNILAC gas stripper generally. As a long term test could not be conducted so far, the service life of these valves under operational conditions is still unknown.

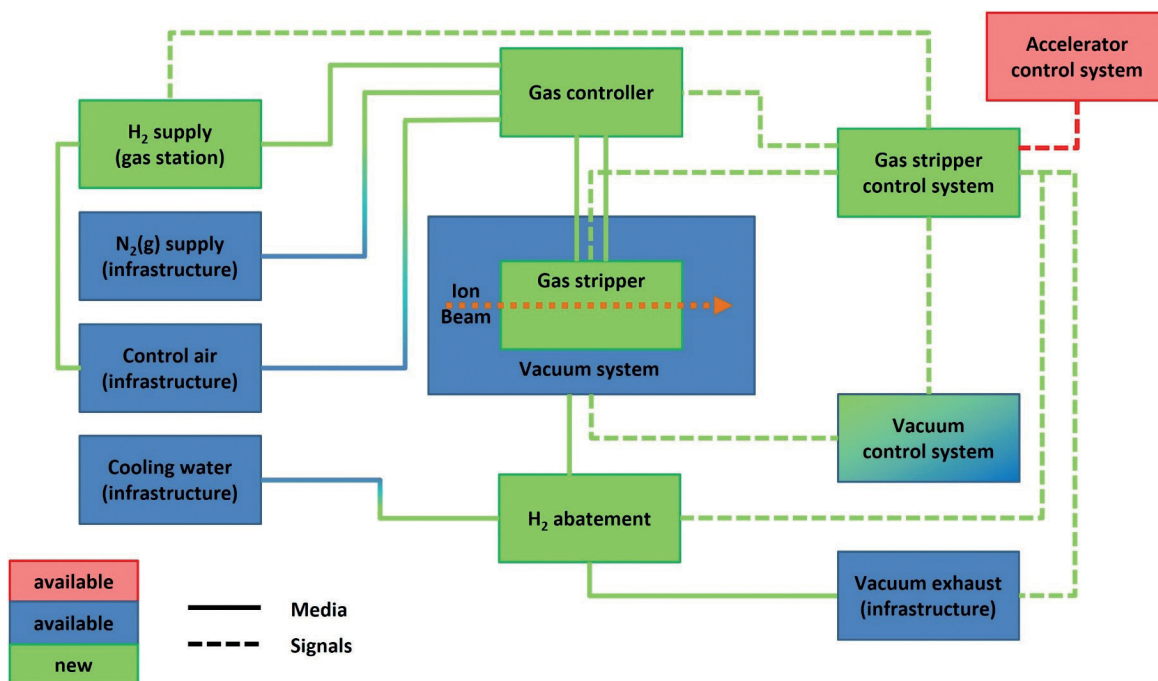


Figure 99. Schematic overview of the pulsed gas stripper system concept. All new components and components requiring major adaptations or extensions are shown in green.

After the valve problem was presumably solved, the exhaust problem was approached by an extensive market and technology survey. It was found that there is a standard technical solution called gas abatement. This is widely used especially in the semiconductor industry to get rid of toxic or combustible gases incorporated in the vacuum exhaust of their production lines. Typically, a flame or another hot process in oxidizing environment and successive wet gas washers are applied to dispose all unwanted components of the exhaust gas. For the simple abatement of hydrogen, a facility was found that uses a catalytic process at low temperatures, making it much simpler and presumably more safe.

After both show-stoppers were put away, a holistic conceptual design of the pulsed gas stripper system was compiled, including basic ideas how to ensure safety under regular operation conditions. The resulting system setup is shown in Figure 99.

The main components are

- a H<sub>2</sub> gas supply, including a gas station and a pipeline,
- an N<sub>2</sub> gas supply,
- a gas controller, providing stripper gases at different pressures as required by operation,
- a gas stripper control system, divided into fast control for the pulsed valves and slow control for the complete system, featuring high operational safety,
- the gas stripper setup containing the pulsed valves,
- the vacuum system and its control system,
- the H<sub>2</sub> abatement facility,
- the vacuum exhaust ventilation system providing radiation protection filtering,
- the accelerator control system, from which the gas stripper will be directed as an accelerator device, and
- additional media supply (control air, cooling water and electric power).

A more detailed description of the components, relevant requirements and a baseline safety concept was written and distributed to the main departments involved in the realisation.

## Outlook

Approval of the conceptual system and safety design by the involved departments is expected beginning of 2020. Based on this, the next step will be the detailing of the baseline safety concept leading to a comprehensive risk assessment and finally an explosion protection document. In parallel the detailing of the technical system design will be elaborated. Procurement and further steps or decisions will be made only after provisional approval by the authorities and a notified body.

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## 14.6 Operation Infrastructure Support

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

In 2019 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 close collaboration e.g. of using special welding 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.

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

- Production of the 11 drift tubes and stems for the first of series Alvarez tank for the new UNILAC post-stripper and of low level rf-tuners
- Formal qualification of welding procedure for the SIS100 string tests by means of a mock-up, which is rather complicated due to limited space conditions.
- Feasibility test for cutting and welding of flanges of two prototype SIS100 magnetic dipole beam pipe vacuum chambers incl. the required precision control measurements. The prototypes have been successfully cut and welded in preparation of the entire 107 pieces of the SIS100 dipole series that will start in 2020.
- Support of the repair of the LEBT-QQ



Figure 100. Mounting of the HSI-RFQ baskets.

Furthermore, the exchange of 10 baskets containing electrodes and carrier rings for the HSI-RFQ have been constructed, mounted, and assembled in the GSI High Current Injector (see Figure 100).

The 2019 activities of the Galvanic workshop can be summarized in the following way:

- The retrofitting project was restarted under the leading role of the department of campus development. It was shown that besides the optimization of the Galvanic processes, mandatory fire protection measures in and around the Galvanic building have major impact on the project. The planning is ongoing, recommissioning of the Galvanic workshop is planned for end of 2022. All actual Cu plating activities (mainly Alvarez FOS and preparative works for p-Linac) are ongoing in parallel in 2020/21.
- INFN ordered the Cu plating of DTL tanks of the ESS project in Lund. Three additional tanks have been Cu plated successfully in 2019.
- For the p-Linac project a further demo of the CH structure (see Figure 101) was Cu plated successfully.
- The procedure Cu-plating of the Alvarez demo has been defined and pieces were prepared (namely the cathode supports) and ordered
- For the Alvarez FOS a first drift tube was Cu plated with sufficient high quality (see Figure 101) and the preparation of the large scale FOS tank was ongoing.

Several additional activities have been carried out by the technology laboratory:

- A variety of FEM calculations have been performed to investigate mechanical and/or thermal behavior of different components e.g. belonging to the CBM magnet, the SIS100 quadrupole beam pipes, and ion sources.
- Different brazing works have been done using our vacuum oven:
  - 3 cryogenic copper resonators for IAP, Frankfurt,
  - brazing of different beam diagnostic components,
  - tempering work for SIS100,
  - brazing of electric feedthroughs for the cryogenic ion trap experiment of atomic physics.
- The tempering processes of the series of CuBe strips for FAIR stochastic cooling was prepared for 2020.

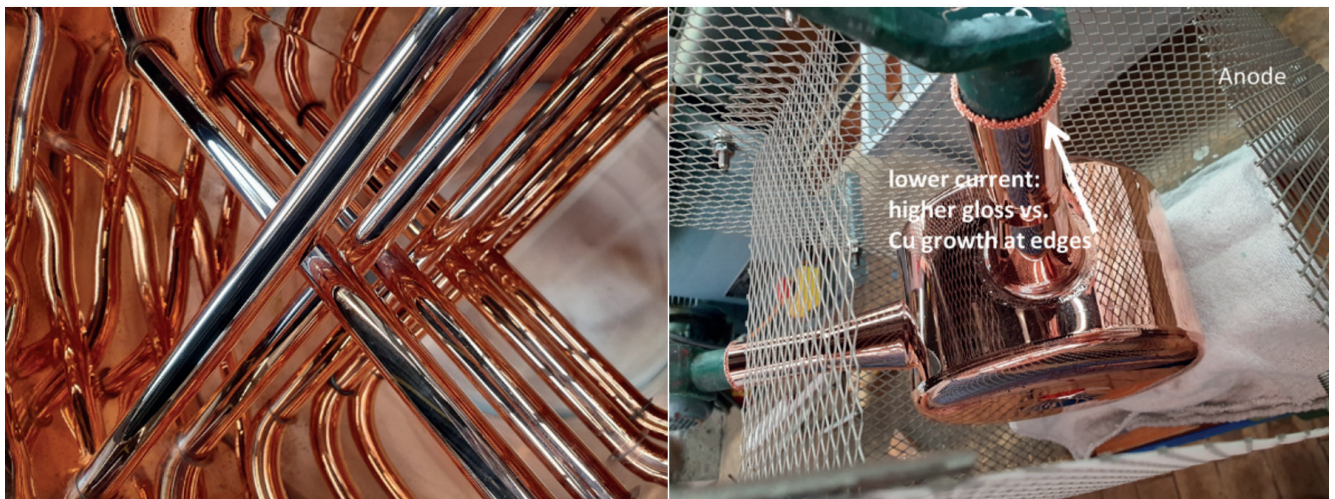


Figure 101. Left side shows the demo structure of the p-Linac to generally test the Cu-plating process for such narrow and small-scale structures. Right side shows the first Alvarez drift tube directly after the plating process still surrounded by the anode structure.

To further improve the quality assurance of our processes with respect to materials selection of alloys, a mobile x-ray fluorescence spectrometer has been purchased which also can be used for chemical analysis of Cu and Ni content of our galvanic baths. To a certain extent it is also possible to measure thickness of thin metal coatings. The equipment will be operating in 2020 after finalizing the formal operating permit.

## 14.7 Contribution to the FAIR project

### 14.7.1 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 (CEA/Saclay), O. Tuske (CEA/Saclay)

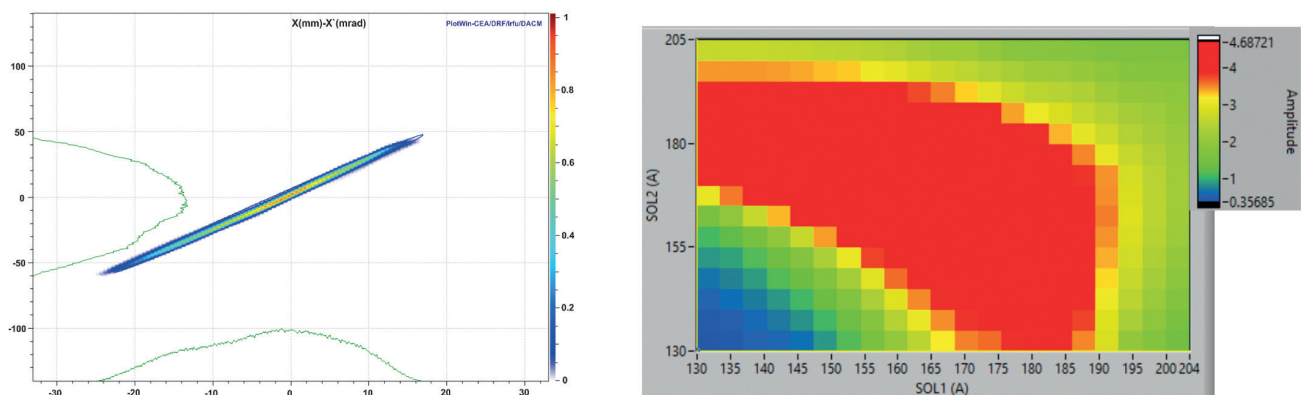


Figure 102. (Left): Emittance measurement behind focus point. (Right): Experimentally measured solenoid field map (created and designed by O. Tuske).

The commissioning of the proton injector including a microwave ion source and a Low Energy Beam Transport (LEBT) is successfully performed at CEA/Saclay. The main specified parameters such as: beam intensity, emittance, proton fraction and stability of the ion source during long run test are in a good agreement with the specifications. The intensity of the proton beam higher than 100 mA was measured with the Faraday cup at the end of the LEBT. The proton fraction higher than 80 % was observed with a Wien filter. The measured normalized rms emittance behind chopper cone is within the specifications and is smaller than  $0.3\pi$  mm mrad and presented in the Figure 102 (left).

Additionally, some new improvements of the control system (designed and developed by CEA employing Labview ) allow to perform the monitoring of the intensity transmission map through the chopper conus as a function of both solenoid values. The measurements of the solenoid field map are shown in the Figure 102 (right). The measured emittance in this area as a function of different solenoids parameters, provides the twiss parameters and therefore allows finding the best fit to the RFQ acceptance.

The stability of the ion source operation was checked during a long run test lasting several weeks. After accepted factory acceptance test the proton injector will be dismantled at CEA/Saclay and transported to GSI, where the final commissioning including another acceptance test will be performed in the new p-Linac building.

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## 14.7.2 Contribution to p-Linac RF

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



Figure 103. LLRF controllers prepared for SAT.

The components for the p-Linac test-stand received from CNRS were tested and documented in a way that this part of the contracts between FAIR, GSI and CNRS is fulfilled. The water-cooled high power loads were characterized in a temperature range between 25 and 35°C thus confirming that they can be used at the foreseen p-Linac cooling water temperature, where the specification was raised from 25 to 29°C. Additionally we tested two custom made high performance measurement transitions between WR 2300 waveguide and Type-N. These allow us to measure low-level parameters of high-power transitions between WR 2300 waveguide and EIA 9-3/16 inch for the p-Linac cavity couplers. To increase the number of possible candidates for waveguide components, we also measured E-Bends, and H-Bends, which are dimension compatible, from 3 manufacturers.

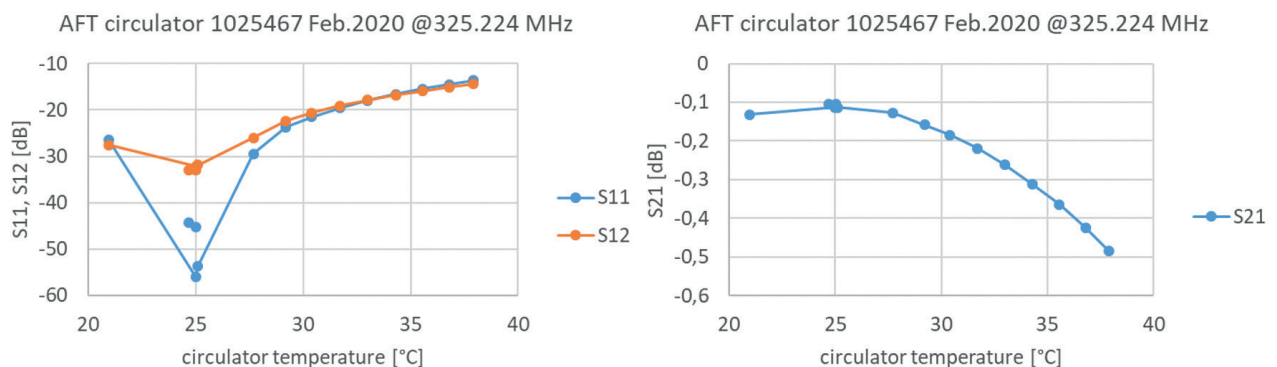


Figure 104. Circulator measurements.

Next we plan to characterize another set of E-Bends, H-Bends, and also flexible waveguides. 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. Currently the work is focusing on the pulse transformers. It is planned to re-establish generating high power RF pulses with the TH2181 Klystron within this year to perform high power component tests. Therefore, the first modulator prototype has to be operational.

So far, 7 Klystrons were delivered [1]. The factory-acceptance-test FAT of Klystron #8 was conducted, however as the documentation is not yet complete, the delivery is delayed. Still there are issues with the operation characteristics of the Klystron ion pumps, where not all pumps want to start, when the pressure rises.

The 10 LLRF controllers including 10 racks were delivered as a FAIR Inkind from I-Tech. Figure 104 shows the preparation for a site-acceptance-test SAT A setup. In 2020 we want to order the high power circulators. For the existing circulator we have to modify the magnetic bias field to shift the operation temperature from 25°C to 29°C. Figure 104 shows the S-parameters  $S_{11}$ ,  $S_{12}$ , and  $S_{21}$ , which are optimized for 25°C as a function of cooling water temperature before the modification.

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## 14.7.3 Development of Stochastic Cooling System for CR

Authors: C. Zhang, C. Dimopoulou, A. Bardonnier, R. Böhm, M. Bräscher, O. Gorda, R. Hettrich, J. Krieg, C. Peschke, A. Stuhl, S. Wunderlich

### Introduction

The 1-2 GHz stochastic cooling system of the Collector Ring (CR) will provide 3D cooling of the hot  $\beta = 0.97$  antiproton beams and of the  $\beta = 0.83$  rare isotope beams (RIBs) for enabling the planned experiments at HESR downstream. In 2019, considerable progress has been made, especially with respect to both the cryogenic plunging Pick-Up (PU) and the Palmer PU. Some highlights are summarized as follows.

Cryogenic plunging PU: successful cryotest - complete concept converged - motor drive units in procurement

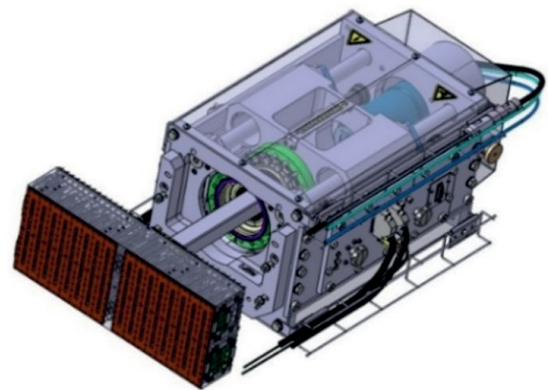
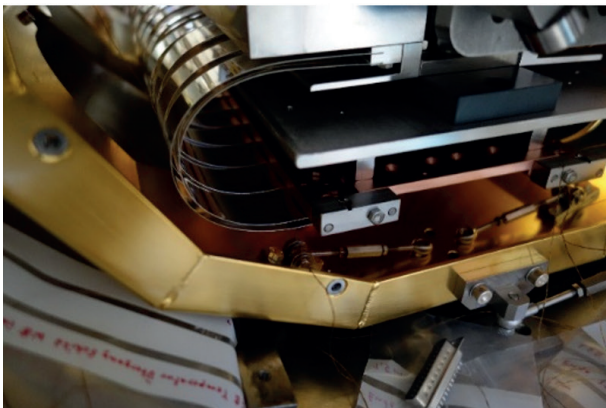


Figure 105. Cryogenic plunging PU with plunging foils for the cryotest (left) and motor drive unit for the cryogenic plunging PU (right).

From the technical point of view, the cryogenic plunging part of the slotline PUs is most challenging in the whole system. To benchmark the full design concept, intensive cryotests have been carried out in the prototype PU tank at the GSI test bench. The mechanical assembly was verified successfully. Further improvements are underway, e.g. a rotatable tank between horizontal and vertical configuration. The vacuum/cryogenic performance met the design goals well. With reduced complexity, the thermal conduction (and hence the temperature distribution) inside the complete PU is satisfactory. The measured temperature on the electrode modules is  $\leq 40$  K. Furthermore, the final version of the plunging Ag/CuBe foils has passed the durability tests. So, the cryogenic plunging PU concept has converged.

Another key component of this PU, the linear motor drive unit, has reached its final design (see Figure 105 on the right side) after intensive testing over many years. The series of 16 motor drive units are under manufacturing/procurement.

## Palmer PU for pre-cooling of RIBs: ready and accepted, to be tested with beam at Forschungszentrum Jülich (FZJ)

In 2019, the vacuum tank (see Figure 106) and the inner structure (Faltin electrode rails) of the Palmer PU, have been manufactured and successfully undergone acceptance tests at GSI. This is the first completed major component of the CR SC system. In 2020, the Palmer PU will be integrated into the COSY storage ring at the FZJ. In joint efforts with FZJ experts, its Rf response in the 1-2 GHz band can be then tested/benchmarked with a  $\beta = 0.83$  COSY proton beam. Ions at this velocity are recently not available at GSI.



Figure 106. Palmer PU tank at GSI.

Last but not least, the microwave damping tubes have been ordered. A prototype CR quadrupole-sextupole chamber has been manufactured at BINP. After the shipment of this chamber to GSI, the assembly of the damping tubes can be tested.

## 14.7.4 The laser cooling lab

Author: Danyal Winters

Due to the refurbishment of the laboratories in the SE-building, it has been decided that a new small lab (~24 m<sup>2</sup>) was needed for the components required for laser cooling at the SIS100. The best-suited place was found to be on the roof of the ESR. The lab is equipped with air cooling and ventilation systems to allow for fresh/clean clear air, low amounts of dust particles (using filters), and a controlled temperature. Inside the lab, important and valuable components for the laser beamline – required for laser beam transport to the SIS100 accelerator – will be tested and stored, as well as small vacuum components, detector systems, and control systems.

## 15. Annex

All publications of the GSI in the year 2019 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>.

All reports of student's works and reports to grants of GSI related to the year 2019 are also published in the publications database within the series GSI Short Reports [https://repository.gsi.de/search?ln=de&p=088\\_a%3A%22GSI+short+reports%22&f=&action\\_search=Suchen&c=GSI+Institutional+Repository&sf=&so=d&rm=&rg=100&sc=0&of=hb](https://repository.gsi.de/search?ln=de&p=088_a%3A%22GSI+short+reports%22&f=&action_search=Suchen&c=GSI+Institutional+Repository&sf=&so=d&rm=&rg=100&sc=0&of=hb), linked at the starting page at the GSI Repository.

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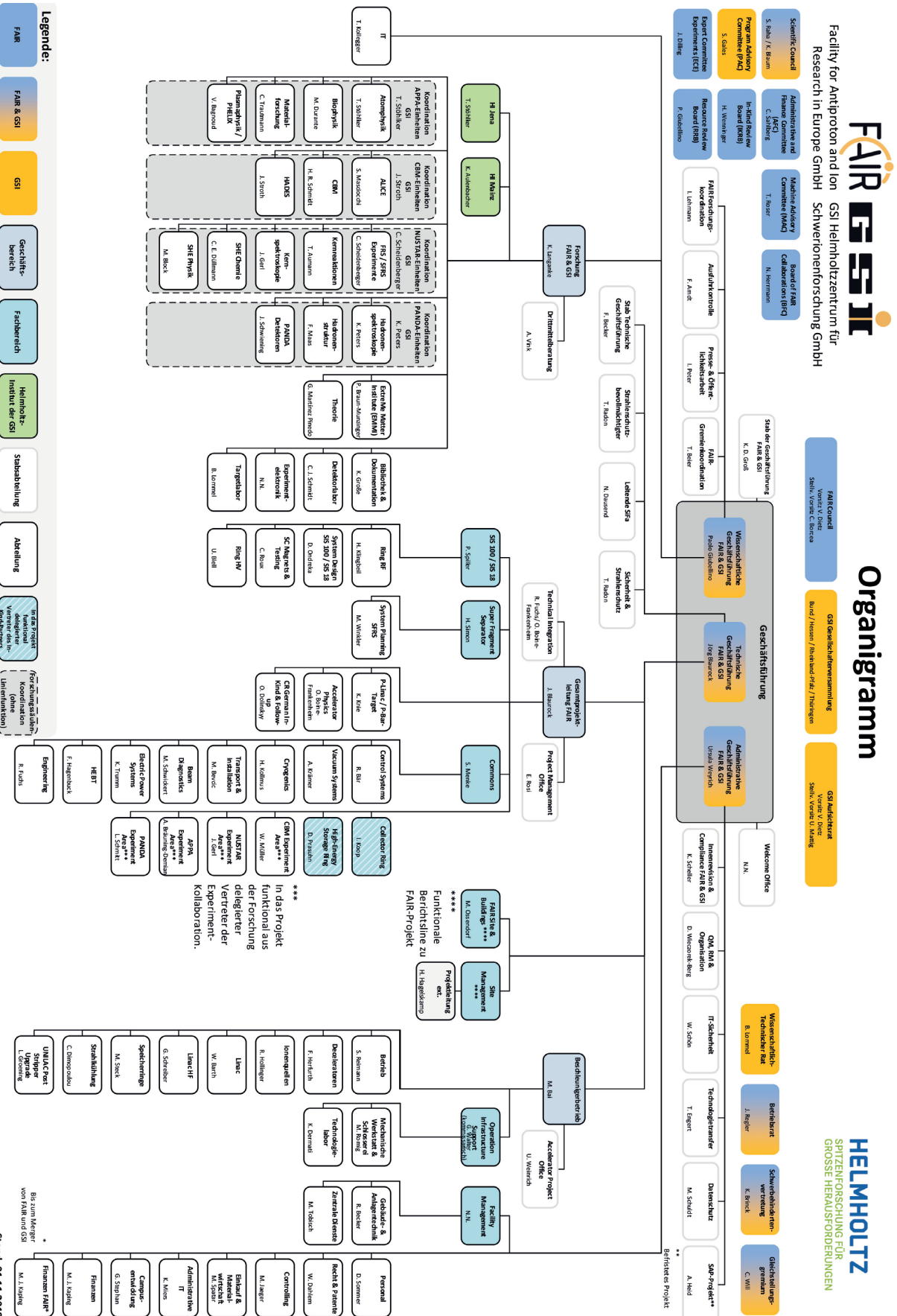
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# 15.2 Organisational chart





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 research in the disciplines of hadron and nuclear physics, nuclear astrophysics, atomic physics, plasma physics, materials research as well as biophysics, radiation biology, space research, and medical technology.

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

