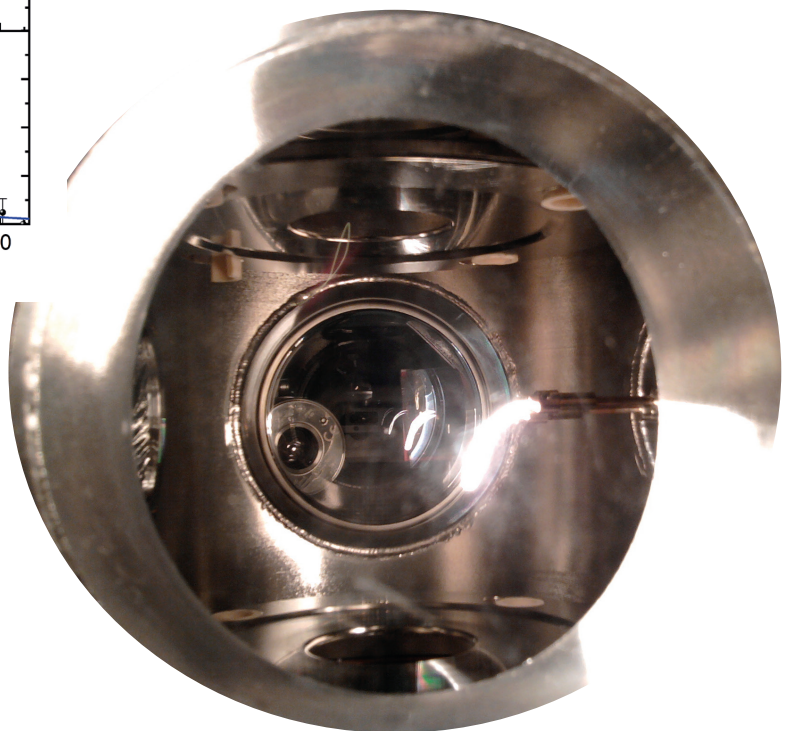
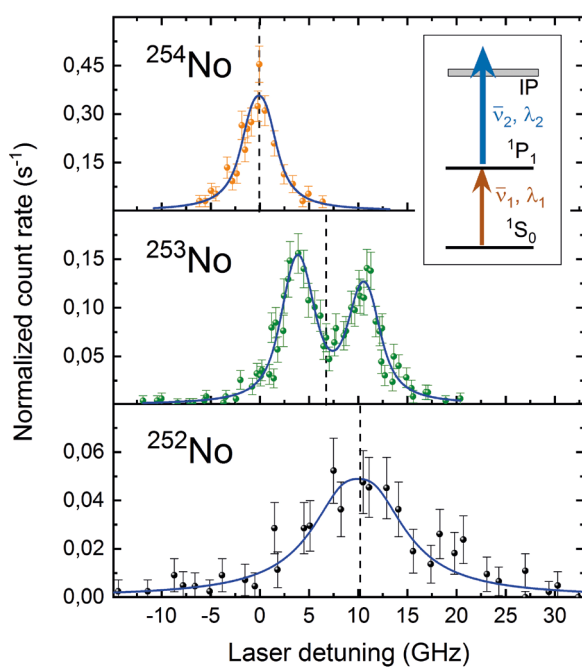


# GSI-FAIR SCIENTIFIC REPORT 2018

An overview of the 2018 scientific and technology achievements



## Cover

The photograph shows the heart of the "RADRIS" apparatus used for laser spectroscopy on the heavy element Nobelium. The rare radioisotopes of this heavy element were made on SHIP and separated from the beam. Then they are braked in high purity argon gas and collected on a Ta wire. By briefly heating to about 1200 °C (neutral) Nobelium atoms are evaporated and irradiated with laser light. Nobelium ions generated by resonance ionization are then transported up to a detector where they are detected by their radioactive decay. The measurements provide information on the atomic structure of Nobelium, but also allow the determination of the size and shape of Nobelium nuclei studied.

See page 45 in this report

Text by M. Block/GSI, figure by S. Raeder/GSI, photo by M. Laatiaoui/GSI



GSI REPORT 2019-1

# **GSI-FAIR SCIENTIFIC REPORT 2018**

An overview of the 2018 scientific and technology achievements

## 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

In June 2018 after several years of accelerator upgrade and maintenance, the GSI accelerators resumed operation and the FAIR Phase-0 research program started. The objectives of the FAIR Phase-0 research program, which is planned with three months per year, are to allow for fore-front research in advance of FAIR by employing detector components developed for FAIR and exploiting the upgraded GSI accelerator facilities including the newly installed CRYRING. The FAIR Phase-0 research program will increase the visibility of FAIR research and further expand the FAIR science community, in particular by training young scientists.

Initially, the beam time campaign started well in June and a number of excellent measurements on atomic structure and precise mass determination of heavy nuclei have been performed. After three weeks the beam time campaign was stopped for technical reasons and the experimental beam time period had to be shifted to February 2019. Following the necessary repair works, the re-commissioning of the GSI accelerator facilities was successfully resumed by carrying out an engineering run in November 2018.

The scientific activities of the research division were concentrated on the research and development of FAIR detectors and the preparation of experimental beam times. Since the experimental beam time in 2018 was rather short, other experimental infrastructures like CERN and RIKEN have been used for experiments and detector tests. Some outstanding results are described in this report:

Investigations of the hyperfine splitting (hfs) in highly charged ions provide an access to the bound-state QED effects in the presence of strong electric and magnetic nuclear field. However, the QED contribution appears to be obscured by the Bohr-Weisskopf (nuclear magnetization distribution) effect. In order to overcome this problem, it is proposed to measure the specific difference of the hfs values in hydrogenlike and lithiumlike ions with the same nucleus. Such data has been measured for  $^{209}\text{Bi}$  lately, but it has turned out that the theoretical and the experimental values are  $7\sigma$  apart. This finding, dubbed 'hyperfine puzzle', has been resolved by nuclear magnetic resonance measurements of bismuth nitrate and sophisticated QED calculations to extract the value of the nuclear magnetic moment  $\mu_I$  of  $^{209}\text{Bi}$ . It turned out that  $\mu_I$  ( $^{209}\text{Bi}$ ) is much smaller than the tabulated value used previously.

In an experiment towards laser-driven plasma acceleration, performed by GSI, HI Jena and Frankfurt University, a target was used consisting out of nanowires placed perpendicular to the surface. The target was developed in collaboration with the materials science group. The resulting particle density after laser irradiation was measured to be a factor of 30 higher than with a normal target and the energy increased by a factor of 2 to 2.5.

The biophysics group has studied the increased biological effectiveness of ultrasoft X-rays compared to "normal" high-energy X-radiation. Ultrasoft X-Rays produce damage in a smaller volume, this effect is also observed for particle radiation.

A highlight of the HADES collaboration is the measurement of virtual photons emitted from the hot and dense overlap zone in Au+Au collisions at 1.23 GeV/u. Since the photons immediately decouple from the strongly interacting matter, this measurement yields direct information on the densities and temperatures reached in the fireball.

The excitation spectra of atomic energy levels of for three different nobelium isotopes  $^{252-254}\text{No}$  have been measured by means of laser spectroscopy at SHIP. These measurements together with sophisticated theoretical calculations provided insight into the evolution of nuclear deformations of the investigated nobelium isotopes.

Findings of the theory group suggest that the role of muons in supernova explosions needs to be reassessed: international research teams showed in model calculations that the creation muons influence the processes during super nova explosions.

In the accelerator division the demonstrator of a superconducting continuous wave linear accelerator, a superconducting CH cavity, was successfully tested with an ion beam from the high charge injector (HLI). Such an accelerator would open up new possibilities for materials science and research with super-heavy elements.

On the FAIR site tremendous progress has been made. After the start of the excavation activities in the summer of 2017, the concrete works in the first section of the SIS100 tunnel have started on August, 2018. The construction is progressing rapidly, which is documented regularly with drone videos and presented to the public on the website. Also in purchasing the FAIR accelerator components important milestones have also been achieved.

In preparation for the fourth program-oriented funding period (POF IV) within the Helmholtz Association, GSI with its sites in Darmstadt, Jena and Mainz was scientifically evaluated in November 2017. An international expert committee chaired by Prof. Hideto En ' Yo, director of the RIKEN Nishina Center, Japan, assessed the contributions of GSI Campus Darmstadt and the Helmholtz Institutes to the POF programs in the field of Matter and the program Cancer Research (Re-search field Health) and judged them to be "outstanding". In the POF IV period, which will start beginning of 2021, GSI and its Helmholtz institutes will only participate in the Helmholtz research field Matter. While GSI with exception of biophysics and the Helmholtz institutes was exempted from the program oriented funding in the current POF III period, for the upcoming POF IV period GSI will return to the POF process with its in-house research activities and accelerator operations in the frame work of the FAIR Phase-0 research program. Therefore, GSI research will prepare for the strategic evaluation in the POF4 process, which will take place in January 2020.

In 2019 FAIR Phase-0 will be continued with about three months of experimental beam time at the GSI facilities. In parallel, the implementation of the FAIR detectors and accelerators will be ongoing. Also next year GSI will establish a Welcome Office for guests and users of the facility. The preparation of the strategic evaluation in the context of the Helmholtz POF4 process will require a greater effort from the research and the accelerator departments. Simultaneously, the GSI campus will be maintained and upgraded to secure operation of GSI and later FAIR. This includes the construction of new buildings – like the parking house and the FAIR Control Center FCC – but also remediation measures in the existing building structure.

## Beamtime in 2018

Beamtime coordinator: Dr. Daniel Severin

| experiment proposal number | spokes-person      | large scale research facility | target station | experiment topic                                                                                                                                        | main shifts | para-sitic shifts |
|----------------------------|--------------------|-------------------------------|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-------------------|
| U308                       | Alexander Yakushev | UNILAC                        | X8             | First chemical study of element 113 behind TASCA                                                                                                        | 9           | 40                |
| U312                       | Michael Block      | UNILAC                        | Y7             | Direct mass measurements and investigations of isomeric states in Lr and Rf isotopes around the deformed neutron shell closure at N = 152 with SHIPTRAP | 41          | 9                 |
| UMat_Tomut                 | Marilena Tomu      | UNILAC                        | M1,M2, M3, X0  | Materials for high dose, high energy density application- on-line measurements and irradiation experiments                                              | 4           |                   |
| UMat_Wucher                | Andreas Wucher     | UNILAC                        | M1             | MeV-SIMS/SNMS                                                                                                                                           |             | 5                 |
| UMat_Wucher_Molecuulest    | Andreas Wucher     | UNILAC                        | M1             | MeV-SIMS/SNMS with organic molecules                                                                                                                    |             | 5                 |
| UMat_Steydli               | Sébastien Steydli  | UNILAC                        | M1             | Ion-induced outgassing and sputtering of volatile and frozen gases                                                                                      | 7           | 9                 |
| Umat                       | various            | UNILAC                        | X0             | Materials Research                                                                                                                                      | 4           |                   |





## 2. Research of the APPA departments

Coordinator: Prof. Dr. Thomas Stöhlker, Friedrich-Schiller-Universität Jena & GSI  
 Author: Prof. Dr. Thomas Stöhlker

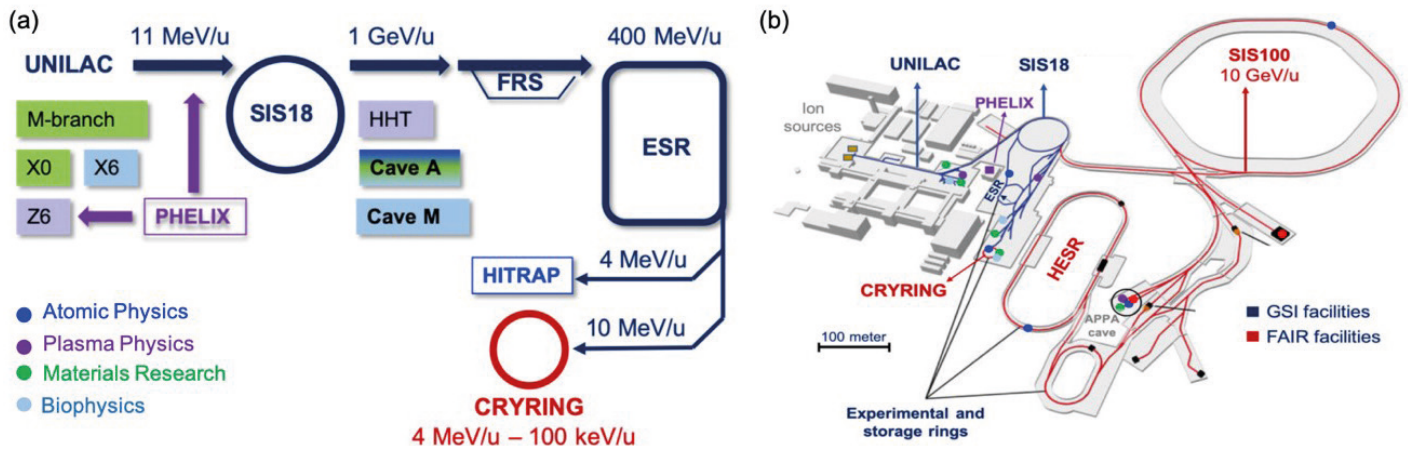


Figure 1. (a) Schematics of current MML-related experimental stations and corresponding typical ion energies. (b) Overview of the ion accelerator facilities and MML-related experimental stations at GSI (blue) and FAIR (red). (Th. Stöhlker et al., Nucl. Instr. Meth. B 365, 680 (2015)).

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

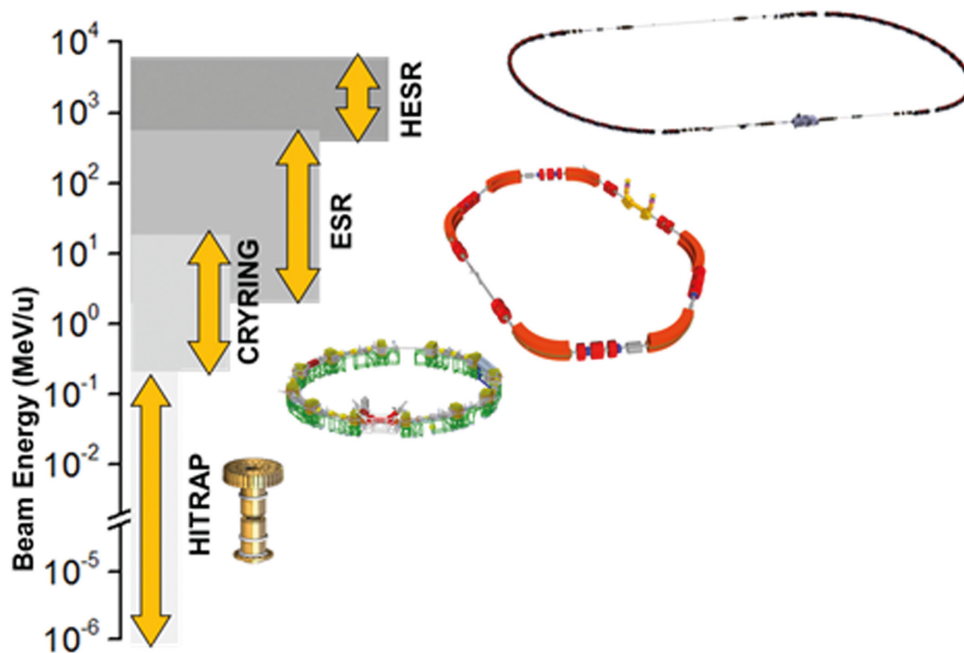


Figure 2. Portfolio of trapping and storage rings available for precision experiments in the realm of atomic and fundamental physics.

In close cooperation with scientists from all over the world, and especially within the framework of the SPARC collaboration, which is a part of the APPA research pillar at FAIR, the working groups of the Atomic Physics Department of GSI concentrate 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 / HITRAP (part of the modularized FAIR facility, see Figure 2) 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 / HITRAP is: ions can be provided over a wide energy range from rest in the laboratory up to relativistic velocities of approximately 70% speed of light. By the future HESR storage ring, the energy range will be further extended to highly relativistic energies ( $\gamma$ -factor up to 6), open up to now unprecedented, unique research opportunities. Finally, the combination with the fragment separator FRS allows to extend the research spectrum to exotic isotopes. All together, these unique research opportunities allow for a broad 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 (potentially reaching the Schwinger limit). In addition, atomic physics research at GSI extends to neighbouring fields such as accelerator physics, plasma physics, and especially atomic and nuclear astrophysics. In order to reach their research goals, particular important activities of the Atomic Physics Division are related to the development and implementation of novel, state of the art instrumentation (such as internal targets, 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.

Note for all the research activities discussed in the following, the Atomic Physics Department has teamed up with the Helmholtz Institute Jena, a research institute of GSI at the campus of the Friedrich-Schiller University of Jena, which partially even took the lead in some projects.

## Highlights in 2018

In the following some selected research projects and research highlights are presented,

### CRYRING commissioning

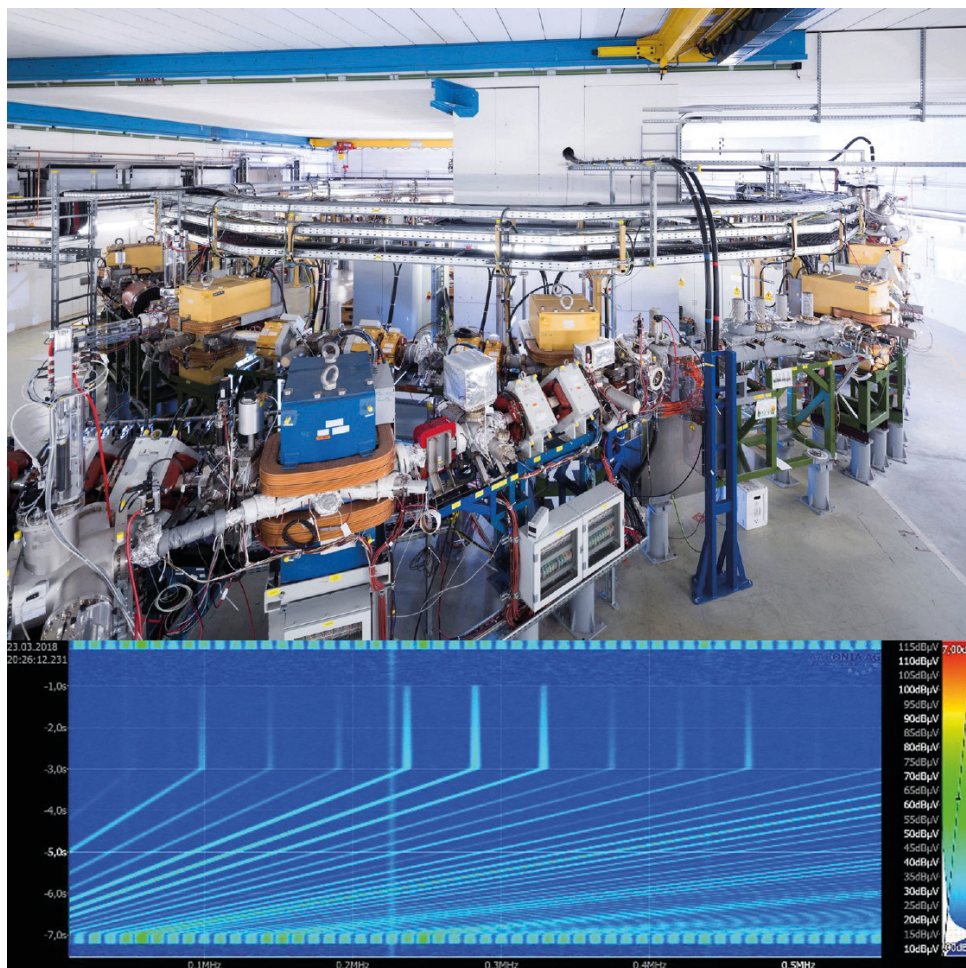


Figure 3. (top) The CRYRING (J. Hosan / GSI Helmholtzzentrum für Schwerionenforschung). (bottom) The figure above shows a Schottky waterfall spectrum of  $\text{Mg}^+$  ions injected at 1.66 keV/u and accelerated to 32 keV/u, measured in a wide range over many harmonics of the circulation frequency. Time is running from bottom to top: one can see the injection and bunching up to -7 s, acceleration between -7 s and -3 s and then  $\text{Mg}^+$  stored for 2 s at 32 keV/u. At -1 s the beam is dumped and the next cycle starts with injection.

During the last few periods of commissioning with beam, the CRYRING@ESR team demonstrated the injection, storage and acceleration of several ion species from the local injector. In the most recent commissioning period during March 2018,  $\text{H}_2^+$  ions were injected at 300 keV/u and accelerated to 24 MeV/u, i.e. maximum rigidity, with a dipole ramping rate of 1 T/s. An exponential decay constant of some 5 seconds was observed for the stored ion current. Moreover, injection of ions at low energy and large  $m/q$  ratio, directly from ion source potential, was also demonstrated in March for the first time.  $\text{Ar}^+$  and  $\text{Mg}^+$  were produced at 40 keV/q (1.0 and 1.67 keV/nucleon, respectively) and injected into the ring without acceleration by the radio frequency quadrupoles (RFQ). In the ring they were accelerated to several tens of keV/nucleon, corresponding to roughly a third of the ring's rigidity. An exponential decay constant of a few seconds, similar to  $\text{H}_2^+$ , was observed also in this case. Therefore, first experiments, such as laser spectroscopy of stored  $\text{Mg}^+$  ions, can be performed in the near future.



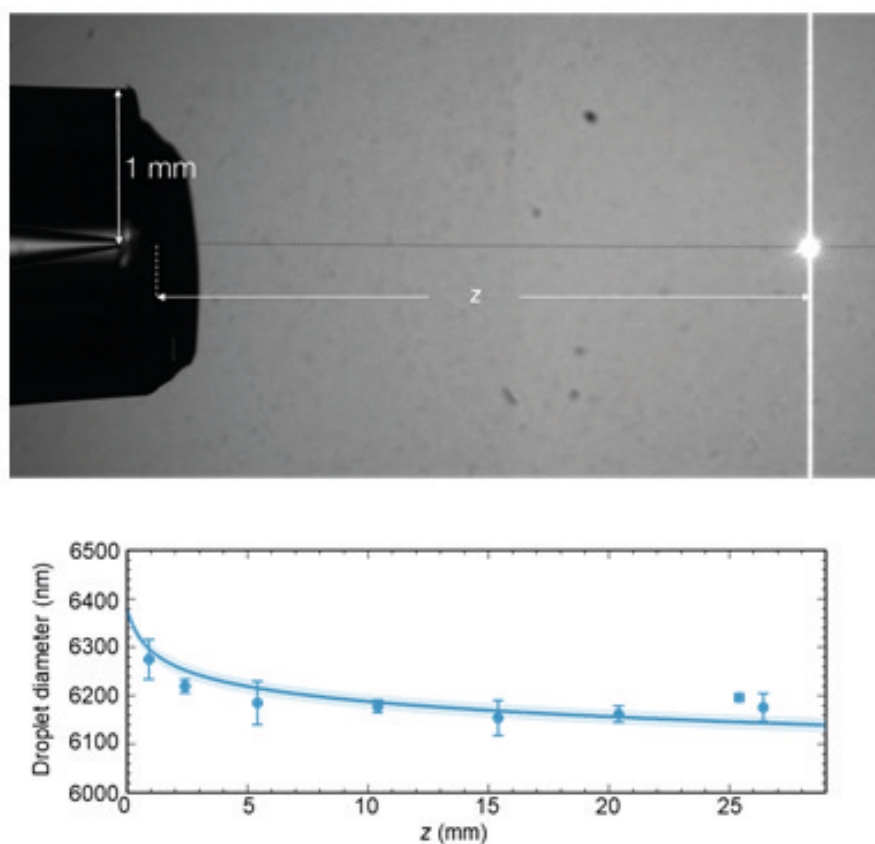


Figure 4. Tiny water droplets that travel in vacuum shrink proportionally as they evaporatively cool. A new technique exploiting the changes in the interference pattern in the light scattered by the droplets now allowed the direct measure of their size with nanometer precision. Using this size to calculate the droplet temperature it was showed that the droplets cooled down to  $-42.550$  C, the lowest water temperature measured to date.

### Precision approach spotted coldest liquid water ever made

Water can exist in a liquid state well below its freezing point, but reliably measuring the temperature of such “supercooled” water has proved challenging. At GSI, we have developed a technique that allowed us to make exceptionally accurate measurements. We sprayed micrometre-sized droplets of water into a vacuum. Molecules of water evaporated from the surface of the droplets, making them smaller and colder. The droplets shrink proportionally as they cool, which enabled us to determine the water’s temperature by measuring the droplet size with a laser with 10-nanometre precision. An international collaboration under the lead of the former Helmholtz Young Investigator Group Leader Robert Grisenti thus obtained a water’s temperature of  $-42.6$  °C, the coldest water ever made. Because super-cooled water occurs naturally in Earth’s upper atmosphere, gaining a better understanding of its properties, as well as how and when it transforms into ice, could help develop more-reliable climate models (see Figure 4). This work was done in close collaboration with the Materials Research division of GSI. The work has been published in *Physical Review Letters* followed by various commenting articles in science journals such as *Nature* and *Physics World*.

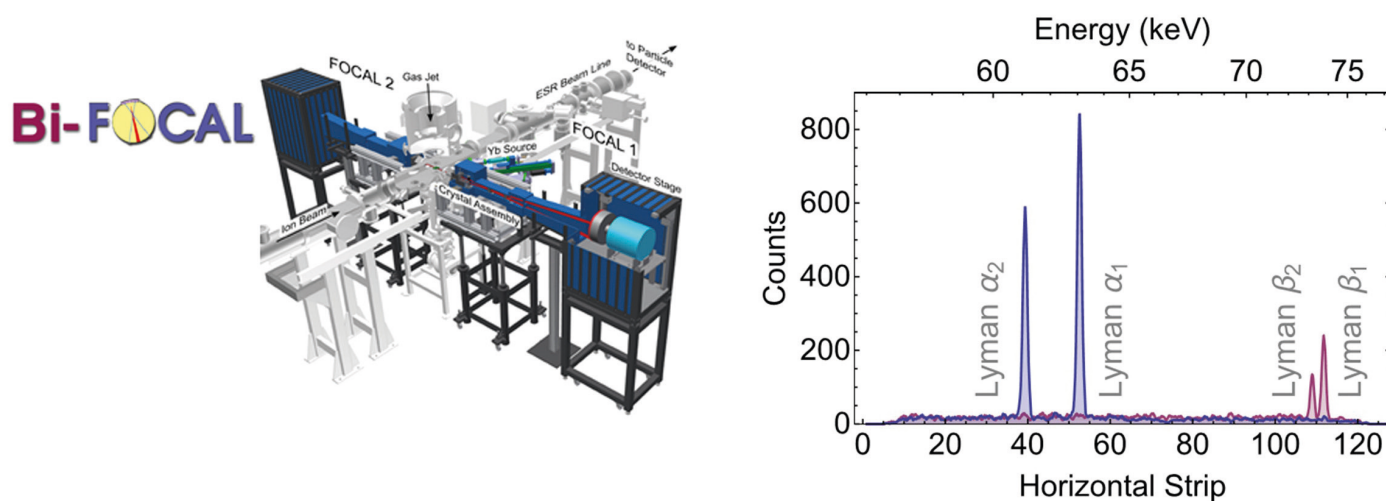


Figure 5. Left: The FOCAL high-precision spectrometer setup at the internal target of the ESR storage ring. FOCAL consists of two transmission crystal spectrometer. At each of the two focal planes, positions sensitive germanium detectors are mounted, enabling to record X-ray events in coincidence with ions having captured one electron ( $\text{Au}^{78+}$ ). Right: X-ray spectrum of hydrogen like gold as recorded by one of the two FOCAL spectrometer.

### 1s Lamb Shift in Hydrogen-like Gold

High-resolution spectroscopy of ground-state transitions in highly-charged high-Z ions at the ESR storage ring is demonstrated to be feasible. The method has been applied for the measurement of the 1s Lamb shift in hydrogen-like gold ( $\text{Au}^{78+}$ ) through spectroscopy of the Lyman x-rays. This measurement represents the first result obtained for a high-Z element using high-resolution wavelength-dispersive spectroscopy in the hard x-ray regime, paving the way for sensitivity to higher-order QED effects. The experiment was performed in 2012, one of the very last experiments at the ESR.

### Hyperfine-puzzle solved?

The results of the measurements on highly charged bismuth ions  $^{209}\text{Bi}$ , which appeared last year [J. Ullmann et al., *Nature Communications* 8, 15484 (2017)] are showing a large deviation from the theoretical expectations. This has been referred to as the “Hyperfine-Puzzle” of bound state-QED. In a most recent publication from Skripnikov et al., this puzzle has been claimed to be resolved. The value of the nuclear magnetic moment seems to have a strong influence on the final theoretical prediction and the discrepancy might be caused by an inaccurate value of the tabulated nuclear magnetic moment ( $\mu_N$ ) of  $^{209}\text{Bi}$ . A new way to disentangle this dependence would be to measure the magnetic moment on the hydrogen-like ion in a trap or to measure the hyperfine splitting in another bismuth isotope by direct laser spectroscopy at the ESR. Both ways are in pursuit by the atomic physics at GSI.

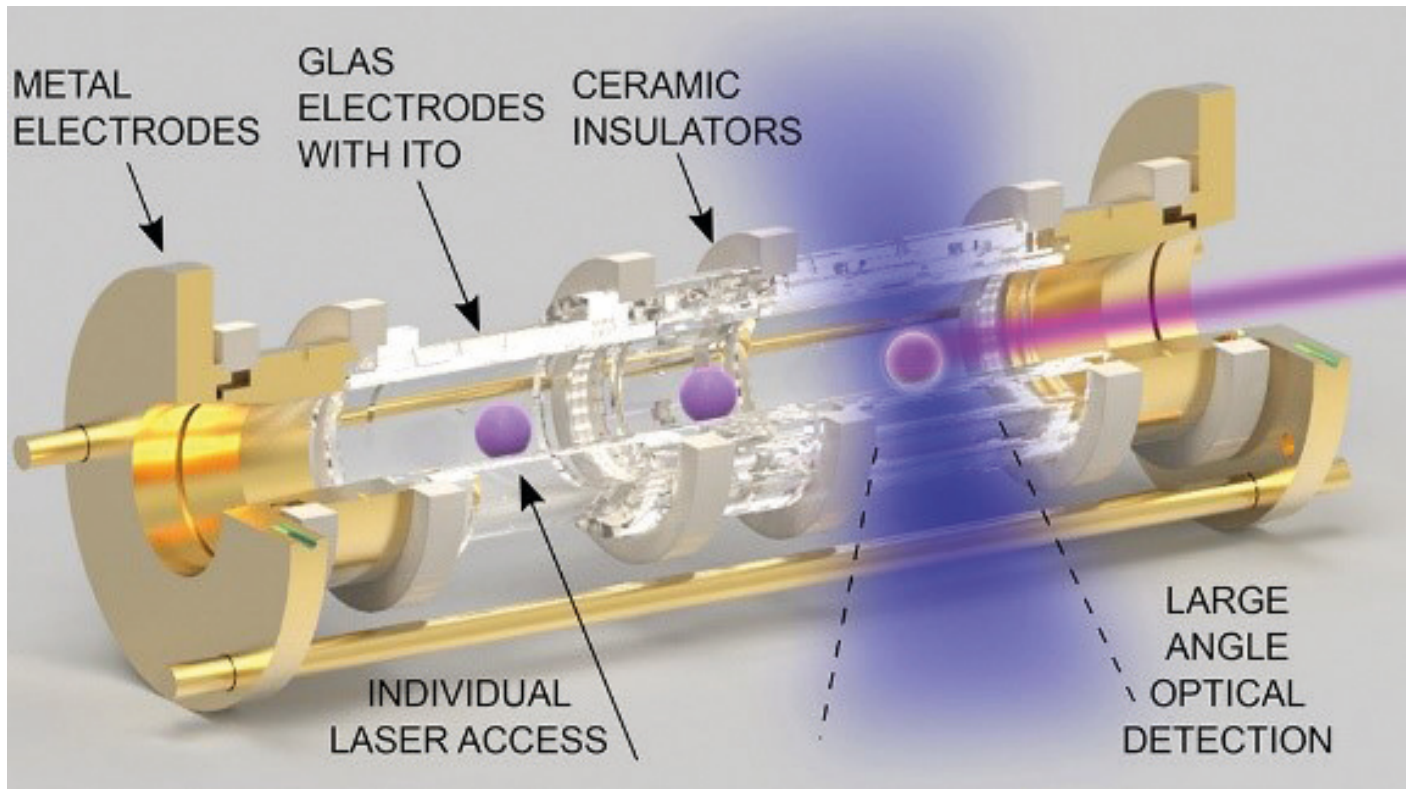


Figure 6. Artist's view of the Penning trap with glass electrodes for large-angle optical access to stored ions. The glass electrodes are covered with a thin conductive ITO layer and produce a highly harmonic trapping potential.

### Progress towards trapping of heavy highly charged ions at HITRAP

At HITRAP, the ARTEMIS highly charged ions experiment has produced the first ion liquid from highly charged ions by mere thermal cooling in a Penning trap [see Figure 6, S. Ebrahimi et al., *Phys. Rev. A* 98, 023423 (2018)]. Since laser cooling is impossible for highly charged ions, this is an important step towards ion crystals for precision spectroscopy of heavily charged ions (HCI) for tests of QED in extreme fields. Moreover, the ARTEMIS team has developed and employed a novel type of a fully solid yet optically transparent electrode for Penning traps that facilitate precision spectroscopy at solid angles larger than traditional designs by one order of magnitude [M. Wiesel et al., *Rev. Sci. Inst.* 88, 123101 (2017) and has been highlighted as a SciLight DOI: 10.1063/1.5017839].

### "Gamma-factory" at CERN

Beginning of July 2018, for the very first time atoms (lead ions with one electron;  $\text{Pb}^{81+}$ ) were injected into the LHC and accelerated with the maximal beam energy of 6.5 TeV (proton equivalent). A team from the Lebedev Institute Moscow, Atomic Physics Department GSI, and HI Jena provided the design parameters for the stripper foils to enable the production of H-like Pb ions at relativistic energies. This success is the key requirement for the proposed "gamma-factory" at CERN which aims on the creation of laser-like  $\gamma$ -beams and to allow the construction of a  $\gamma\gamma$ -collider. This will open up novel research opportunities in the realm of atomic and fundamental research, complementary to the physics program of SPARC at the FAIR facility.

## Outlook and new developments

### SPARC/APPA



Figure 7. Pixel  $\mu$ -calorimeter developed at the University of Heidelberg.

Beside its substantial contribution to the installation and commissioning of CRYRING, the SPARC collaboration, in strong support by the atomic physics department of GSI, currently focus its efforts on the preparation of first experiments at HITRAP, CRYRING, and the ESR storage ring. These activities comprise installation and upgrade measures of in-ring instrumentation (e.g. particle detectors, internal target) and also the transport of SPARC equipment developed within the framework of APPA R&D (BMBF Verbundforschung) at the German partner universities. For instance, a 64 pixel  $\mu$ -calorimeter system, developed at the University Heidelberg, has been transported and installed at an experimental test side at GSI. For rigours testing of this device to be used in first Lamb-Shift experiments for  $U^{91+}$  at the CRYRING, an Electron-Beam-Ion-Trap, provided by HI Jena and the Swedish partners, has been brought to operation and serves as a source for hard x-rays. A further example is a fiber laser system from the partners at the University Jena which will serve as an intense XUV light source for first laser spectroscopy experiments at CRYRING along with the coupling unit (differential pumping stage) needed to couple the laser beam windowless to the vacuum system of the CRYRING ( $10^{-11}$  mbar).

### Selected publications of 2018

- Goy, C. ; Potenza, M. A. C. ; Dederer, S. ; et al.: **Shrinking of Rapidly Evaporating Water Microdroplets Reveals their Extreme Supercooling**. *Physical review letters* 120(1), 015501 (2018) DOI:10.1103/PhysRevLett.120.015501
- Skripnikov, L. V. ; Schmidt, S. ; Ullmann, J. ; et al.: **New Nuclear Magnetic Moment of  $^{209}\text{Bi}$  : Resolving the Bismuth Hyperfine Puzzle**. *Physical review letters* 120(9), 093001 (2018) DOI:10.1103/PhysRevLett.120.093001
- Gassner, T. ; Trassinelli, M. ; Heß, R. ; et al.: **Wavelength-dispersive spectroscopy in the hard x-ray regime of a heavy highly-charged ion: the 1 s Lamb shift in hydrogen-like gold**. *New journal of physics* 20(7), 073033 (2018) DOI:10.1088/1367-2630/aad01d

### For more information to the activities of HI Jena see also

- Helmholtz Institut Jena. ; Günther, M. ; Volotka, A. (Ed.): **Annual Report 2018**. Jena, Darmstadt : Helmholtz Institut Jena / GSI 96 p. (2019) DOI:10.15120/GSI-2019-00643



## 2.2 Department Materials Research

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

The scientific interests of the Materials Research Department cover a broad variety of topics related to the interaction of energetic ions with solids such as damage effects at materials surface and bulk, track formation and phase transition processes, and radiation hardness of materials in extreme environments including high pressure. Our research activities particularly concentrate on functional materials for beam-intercepting devices and components to be used at FAIR (e.g. Super-FRS target wheel, collimators and beam dumps).

The GSI ion beams are also applied as structuring tool for the production of nanostructures by ion-track technology. The group provides extensive know-how in chemical etching of ion tracks, electrochemical deposition, and surface modification techniques to synthesize and characterize tailored nanochannels and nanowires.

The Materials Research Department operates several beamlines including (i) Cave A at SIS18 for irradiations of mm thick samples as well as at the UNILAC (ii) the M-branch for online and in situ monitoring of beam induced effects in materials by numerous spectroscopic and microscopic techniques, (iii) the beamline X0 for high through-put irradiations of up to 100  $\mu\text{m}$  thick samples including sample exposure to single ions, and (iv) the heavy ion microprobe for targeted irradiations (precision below 1  $\mu\text{m}$ ) of biological cells and electronic devices for space applications.

### Activities in 2018

The MAT-Science Week (April 24 -27, 2018) at GSI organized by our Department brought together more than 100 scientists from around the world involved in materials science with ion beams (from eV up to GeV) and related applied fields such as solid state physics, mineralogy, geophysics, nanoscience, and biochemistry. The workshop provided a platform to discuss upcoming opportunities at the future APPA facilities at FAIR.

In June 2018 during a short beamtime Xe and Ca ions were provided at the UNILAC for several user groups.

A new Field Emission Scanning Electron Microscope (Zeiss, Gemini 500) was installed with imaging resolution in the nm range and featuring a broad detector portfolio, elemental analysis, and scanning transmission mode.

### Highlights in 2018

**Radiation damage** studies in 2018 covered beam-induced defect phenomena in various materials (e.g. cerium-, thorium- and uranium oxides, pyrochlores and other complex oxides, single phase concentrated solid solution alloys, amorphous silicon nitride and silicon dioxide, quartz, various polymer species) and discussed questions such as grain size and thickness effects, nanoscale density variations and local order and disorder in tracks, and track annealing behaviour.



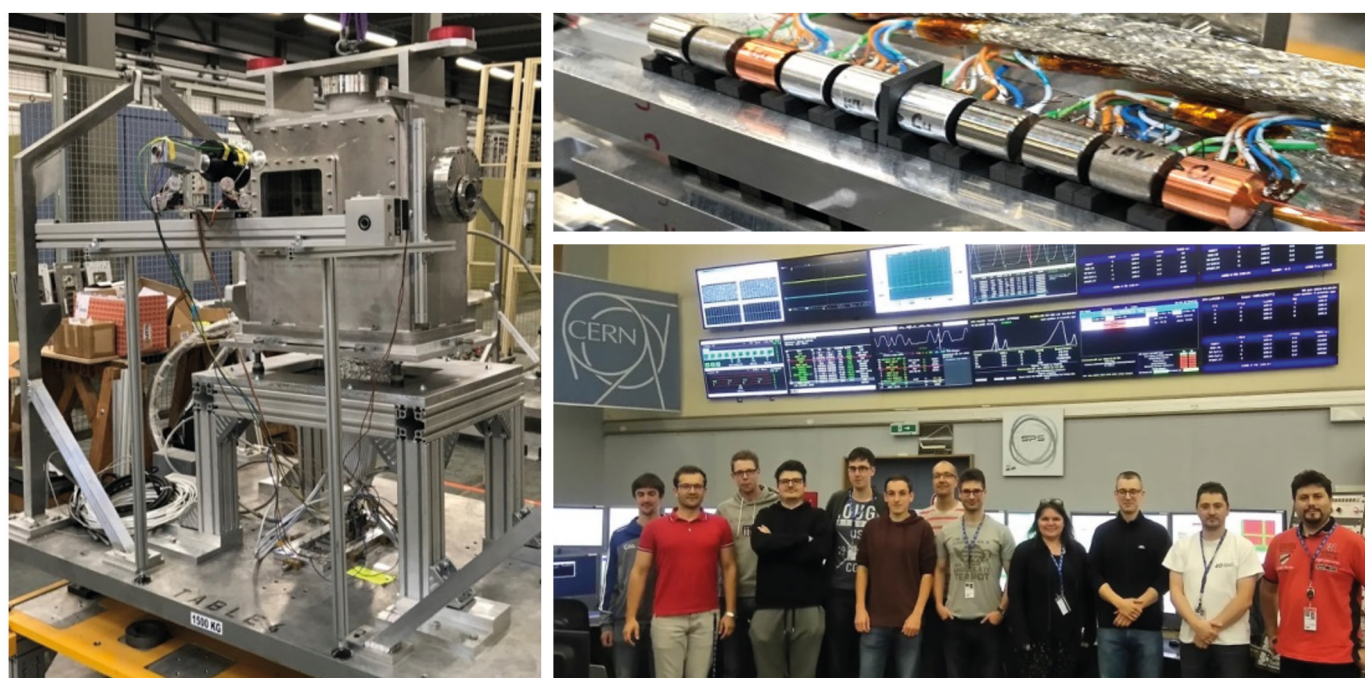


Figure 8. Experimental set-up at HiRadMat beamline at CERN (left); series of cylindrical samples with attached strain gauges for online monitoring (top right); GSI and CERN team (bottom right).

The research activities of the group concentrated particularly on [carbon-based material](#) candidates for future FAIR and LHC components. Carbon materials are considered to have favourable properties such as low-Z composition, low cost, good thermo-mechanical properties and excellent radiation hardness. The investigations focused on the question how ion irradiation affects the structure and under which conditions degradations of thermal and mechanical properties occur that might limit reliable performance. In a dedicated irradiation experiment (FlexMat) at the CERN user facility HiRadMat, it was tested how high-power target and beam dump materials respond to pressure waves induced by intense 440 GeV proton beams. By means of Laser Doppler vibrometers, beam-induced surface velocities were recorded and analysed as a function of time. The microstructural properties are shown to have a significant influence on the dynamic response (pressure wave propagation and damping) under high-power beam impacts. The experimental data are extremely helpful for benchmarking respective calculations by finite element simulations.

Another focus of 2018 were [desorption and sputtering processes](#) under swift heavy ion bombardment investigated by mass spectrometry in combination with time-of-flight measurements (ionic species) and laser post-ionization of neutral clusters by a pulsed VUV laser [Breuer et al, NIMB 435 (2018) 101, DOI:10.1016/j.nimb.2017.10.019]. Such experiments are relevant for many different topics including processes of cosmic radiation with interstellar dust and degradation of the dynamic vacuum conditions in accelerator sections, where beam losses stimulate extensive release of gas, e.g. from the wall of the beam tube or vacuum chamber.

Research activities based on [ion-track nanotechnology](#) in collaboration with various national and international teams aimed at exploiting synthetic nanochannels as sensors and as model system for ion-channels in biomembranes. We investigated in particular nanofluidic transport phenomena through track-etched channels modified by a chemical process or coated by atomic layer deposition. Nanowire arrays and highly interconnected nanowire networks with tailored parameters were developed for thermoelectrical, photoelectrochemical, catalytical and plasmonic applications. Magneto-transport properties were measured for nanowires based on the topological insulator  $\text{Bi}_2\text{Te}_3$ . The application of ZnO and  $\text{Cu}_2\text{O}$  nanowire networks as photoelectrochemical nanoelectrodes for harvesting solar energy via water splitting was explored.

## Release of large polycyclic aromatic hydrocarbons by cosmic rays from interstellar dust

Top-down chemistry is believed to be responsible for the formation of large molecular compounds such as the polycyclic aromatic hydrocarbon-like molecules and the fullerenes observed in the interstellar medium. The release of these large molecules from the parent grains remains an important issue to be investigated. The exposure of dust grains to cosmic radiation during their journey in the interstellar medium is simulated by laboratory experiments probing to what extent electronic sputtering and/or desorption processes induced by high-energy ion projectiles contribute to the creation of large molecular components in space. Carbonaceous dust analogues (soot nanoparticles) were irradiated with 4.8 MeV/u Ca ions, and mass spectra of the ionic and neutral molecular fragments emitted shortly after the impact were monitored. Large molecular fragments were detected, including neutral and ionic polycyclic aromatic hydrocarbons containing up to several tens of carbon atoms, as well as ionic fullerenes. The experiments provide a proof of principle of a top-down scenario involving interaction processes of interstellar dust with high-energy projectiles yielding large molecular compounds observed in space [T. Pino et al., *Astronomy & Astrophysics* 623, A134 (2019) DOI:10.1051/0004-6361/201834855].

## Proton-gated rectification regimes in nanofluidic diodes switched by chemical effectors

Nanofluidic devices based on solid-state nanochannels provide excellent control over ionic transport processes for pH-, temperature-, and voltage-regulated molecular devices. In this project, a sugar-regulated pH-responsive nanofluidic diode is presented based on a single, conical-shaped nanochannel decorated with electropolymerized 3-aminophenylboronic acid. It is demonstrated that such nanochannels allow completely different proton-regulated nanofluidic operations including anion-selectivity, cation selectivity, and no selectivity by simply varying the fructose concentration in the electrolyte solution [1].

## Nanowire networks as photoanode model systems for photoelectrochemical applications

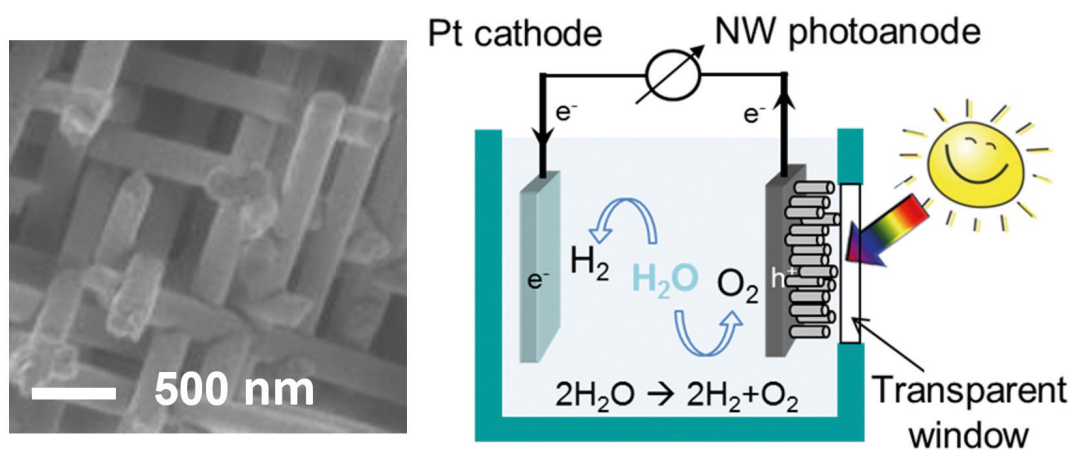


Figure 9. Right: mechanically stable ZnO nanowire network fabricated by electrodeposition in track-etched membrane irradiated under 4 different tilting angles. Left: principle of solar energy harvesting using nanostructures as photo-anode. The Project received DFG funding (FOR 1583 and SPP 1613).

Nanowire-based structures are of great interest for photo-electrochemical water splitting devices for the production of  $H_2$  as renewable solar fuel. By performing irradiations under tilted beam incidence from different angles and a combining ion-track technology, electrochemical deposition, and atomic layer deposition, hierarchical and self-supporting three-dimensional (3D) networks of pure ZnO- and  $TiO_2$ -coated ZnO nanowires were synthesized and tested regarding their photo-electrochemical efficiency. Due to the improved transport properties of photo-generated charge carriers and faster redox reactions at the surface, such nanowire networks are promising for application as photo-electrodes or in sensing, catalytic, and piezoelectric devices [2].

## Outlook for 2019

During the spring beamtime block various beams (Sn, Au, Ca, Ag and Fe) will be provided at UNILAC. At SIS18 technical tests of high-pressure irradiation equipment and an irradiation campaign for electronic equipment (ESA and other teams) are planned. In the course of 2019, the user platform for material science will be complemented by a new experimental station at the CRYRING, a storage ring which will provide highly or fully stripped ions with adjustable kinetic energy in the range of few keV up to 10 MeV/u. The ion beam will be extracted and used for irradiation experiments in a UHV chamber equipped with in situ analysis. The high charge state of the ions is attractive for material and nanosciences, as the ions deposit enormous potential energy particularly at the sample surface. This new station is of interest for producing nanostructures in 2D and 3D materials.

## Selected publications of 2018

- [1] Pérez-Mitta, G. ; Marmisol, W. A. ; Burr, L. ; et al.: **Proton-Gated Rectification Regimes in Nanofluidic Diodes Switched by Chemical Effectors**. *Small* 14(18), 1703144 (2018) DOI:10.1002/smll.201703144
- [2] Movsesyan, L. ; Maijenburg, A. ; Goethals, N. ; et al.: **ZnO Nanowire Networks as Photoanode Model Systems for Photoelectrochemical Applications**. *Nanomaterials* 8(9), 693 (2018) DOI:10.3390/nano8090693

## 2.3 Department Plasma Physics

Head: Dr. Vincent Bagnoud, Technische Universität Darmstadt & GSI  
 Authors: Dr. Vincent Bagnoud

The plasma physics department is responsible for the maintenance, development, and operation of the plasma physics facilities at GSI, namely the PHELIX laser, the Z6 target station at the UNILAC experimental hall where combined laser and ion experiments can be conducted, and finally the HHT target station at the SIS18 synchrotron. Scientifically, the department does research on proton radiography and on extreme states of matter with ion and laser beams, and its diagnostics. Additionally, the department is involved in various projects aiming at exploring the acceleration of particles with short-pulse lasers.

### Highlights in 2018

In 2018, the experiments with PHELIX have led to the high scientific output for our department. Experiments on laser-driven ion acceleration with a "top hat" beam generated by a phase plate have shown a change in the ion beam energy spectrum towards low energies that require further investigations. In addition, an experimental run dedicated to studying the evolution of the critical plasma density during the interaction of a high-temporal-contrast laser pulse with a solid target was performed. This run demonstrated that target foils as thin as 80 nm remain opaque to the laser during the whole interaction, when the temporal contrast is enhanced by use of plasma mirrors. In addition, time-resolved optical plasma diagnostics have been used during this run, whose data are still being evaluated.

In our activities to develop laser-driven hard x-ray sources for diagnostic applications in high energy density matter experiments at FAIR, we have comprehensively characterized the spectral, angular and spatial properties of thin foil and wire targets over a wide range of relativistic laser intensities. Our experiments at PHELIX have shown robust performance and high x-ray yields in the 20-200 keV spectral range. Achieving source sizes as small as 5 micron, we imaged the rapid hydrodynamic expansion of short-pulse heated thin wire targets with unprecedented spatial resolution. Furthermore, the spatial coherence of this x-ray source is sufficient to allow propagation based x-ray phase contrast imaging XPCI, where the image contrast is formed by gradients in the refractive index, rather than by absorption. In collaboration with the XPCI group from the Erlangen Center for Astrophysics ECAP, the grating-based Talbot scheme to achieve phase contrast was successfully adapted to work with the x-ray source at PHELIX.

PHELIX users from Helmholtz-Zentrum Dresden-Rossendorf have continued their study on the generation of nanodiamonds and the collection of nanodiamonds after the interaction of an energetic nanosecond pulse with plastic foils. For this run, the diagnostics have been complemented by a VISAR system that brings information on the spatial homogeneity of the interaction and its time scale, and a new diamond catcher based on foams that has been used for the first time.

In experiments of our group at the JETI-40 laser in Jena, ultra-high energy density plasma states were produced by the interaction of high-contrast relativistic laser pulses of the doubled frequency with planar metallic foils. Bulk plasma parameters were investigated by measuring the characteristic x-ray radiation emitted from the target front side. PIC and HD-simulations allowed for getting insight into a spatial and temporal history of plasma parameters and using this knowledge for the X-ray spectra interpretation. Analyses of the obtained spectra demonstrate generation of the plasma states with the bulk electron temperatures above 1 keV and near-solid densities. Using Ti-foils covered with nm-thin Fe-layers we have demonstrated that the thickness of the created keV hot dense plasma doesn't exceed 150 nm.

At our ongoing campaign within the "discovery science" program at the National Ignition Facility the high quality radiography and x-ray scattering data have unequivocally shown that extreme densities (>30-fold compression) were obtained in the hohlraum-driven spherical shell implosions. Both diagnostics indicate a significant increase in the average ionization state compared to standard opacity models, which could be explained by an increase of ionization potential lowering in the strongly coupled regime.



Our campaign concluded with successfully demonstrating X-ray scattering in the collective domain from spherical targets driven to conditions comparable to those predicted in brown dwarfs.

One of the core duties of the department is the operation of the petawatt laser PHELIX for an international user community. In 2018, 51% of the time was used to prepare and to perform experiments for external and internal groups. Over the year, in total 509 shots were recorded as experiment shots in the PHELIX shot data base with a reliability of 96%. Most of the reliability issues were due to hardware problems, which have been identified and solved in between. The largest hardware failure in 2018 concerned the nanosecond frontend. The nanosecond-frontend broke some time before it was supposed to be used in an experiment at Z6. Thanks to the extensive help of colleagues from Luli, France, the beam time took place with almost no delay for the users. All-together PHELIX achieved a very high reliability, even in a complicated environment. To date, PHELIX has achieved ten years of operation. In total, more than 100 experiments were conducted at GSI's large laser facility after the first high energy shot was delivered on target at the combined ion and laser target station at Z6 in May 2008. For this occasion, a small celebration event was organized and approximately 250 employees, guests and former colleagues took the opportunity to visit the PHELIX laser bay before a special scientific colloquium with speakers from all over the world took place.

The largest project currently undertaken in the department is the upgrade of the experimental capabilities at the HHT cave located at the extraction line of the SIS18 synchrotron. The experiments at HHT in the framework of the FAIR Phase-0 Research Program will be conducted along two lines of research: with the PRIOR II proton microscope and with the HIHEX experiments. Both of them are done as forerunner experiments of the HED@FAIR collaboration. Commissioning with ion beams with static and dynamic objects will be done in 2020. In 2018, considering the lessons learned during the first PRIOR experiments with permanent magnets and the problems with beam field quality degradation by ion beam bombardment, a new design of radiation-hard electric quadrupoles have been designed and the in-kind contract with FAIR was finally signed in February, so that the call for tenders for the magnets and its power supplies could be launched. The tendering was successful and the components were ordered to be delivered in 2018. Further on, water cooled cables were ordered and already installed. In collaboration with the Goethe University in Frankfurt, a new pulsed power driver for exploding wires is being developed. Regarding the time plan everything will be installed in time and commissioned end of 2019 and spring 2020, when we have granted beam time for the PRIOR experiments at HHT. For HIHEX, the focus lies on the setup of a vacuum beamline connecting PHELIX to the HHT-cave. In 2018 the planning was finished: laser pulses of 200 J, with a pulse length of 1 ns at 527 nm wavelength will be available for combined high-power laser heavy-ion beam experiments. Thus, laser-driven X-ray sources can serve as diagnostic tool for dense ion generated plasmas, or plasmas are created by the laser and characterized by the proton-radiography capabilities at HHT (PRIOR). The beamline including a frequency doubling station will be constructed and commissioned in the next two years. In parallel, the funding for the target chamber could be secured thanks to the successful application of the universities in Frankfurt/M, Darmstadt and Jena. With a total of 560 k€ the funding is less than half of the project cost as estimated in the Technical Design Report from 2017 for the APPA cave, but it allows producing a reduced-size target chamber, that will be first used at HHT. It is planned to use this chamber from 2021 on at the HHT experimental area for FAIR Phase-0 Experiments including the 100J PHELIX laser beam, and to transfer the chamber later to the APPA cave for the FAIR Day-1 Experiments.

In line with the host lab duties of GSI and FAIR, the department actively coordinates and supports the preparation of the HED@FAIR experiments at FAIR, where significant advance was made in 2018. Substantial progress has been achieved for all working packages relevant for FAIR Day-1 Experiments, as defined by the Technical Board. Concerning the "WP Beam Matching Section (BMS)" connecting the plasma physics infrastructure to the FAIR accelerator in the APPA cave, the Technical Design Report for this part of the ion beam line, consisting of normal conducting magnets, the ion beam diagnostics and the vacuum system, has been approved in February 2018. It is designed to be compatible with the HEBT beam line, as it will consist of the same components. Additionally, by including the ion beam shaping capabilities of the last part of the HEBT beam line, we could reduce the number of the quadrupoles in the beam matching section by three and hence reduce the costs noticeably. With this, the ion-optical layout of the ion beam line is fixed and the process of ordering can start now. For the WP "Final Focusing System (FFS)", a first final design review panel was held at GSI, where severe concerns on the location of the super-conducting current leads and its influence on the magnetic field of the quadrupole were evolved. Hence, we decided to design a new current leads box on side to the quadrupoles to solve these problems. The new design was developed at IHEP, Moscow, during 2018. To save time, the production of

the super conducting cable has started as well as the drawing and manufacturing of the tooling. Finally, the WP "Diagnostic Laser", where a large task is to develop an amplifier module capable of operation at high repetition rate, several important steps have been realized. First, the cooling of laser amplifier discs with a liquid has been simulated successfully, the cooling liquid has been determined and ordered, and the holder for the amplifying glass slabs has been designed and produced. Finally, the planning of the APPA building is becoming more and more detailed. The building itself is fixed, all rooms are defined, during the year most work was done on the integration of the infrastructure. Especially the definition of all cables and the cable routing took a lot of time and several iterations to avoid any conflict with the experimental infrastructure were needed.

## Outlook for 2019

In 2018, our group was successful in participating to several research calls. The four-year-long ATHENA project of the Helmholtz association was officially started. This project supports research in the field of laser-driven particle acceleration. In the upcoming years, ATHENA will provide the research funding for activities towards laser developments at GSI for FAIR and the Helmholtz-Zentrum Dresden-Rossendorf. ATHENA will also help the further development of the LIGHT test stand at the Z6 target station. In collaboration with the Technical University of Darmstadt, a Loewe Center for nuclear photonics was started at the institute for nuclear physics in Darmstadt, for which an enhanced research on the laser-driven neutron generation is envisioned at the PHELIIX facility in the next years.

## Selected publications of 2018

- Tahir, N. A. ; Shutov, A. ; Lomonosov, I. V. ; et al.: **Ion-beam-driven Planetary Physics Research at FAIR**. *The astrophysical journal / Supplement series Supplement series* 238(2), 27 (2018) DOI:10.3847/1538-4365/aadd4c
- Hiltz, P. ; Ostermayr, T. M. ; Huebl, A. ; et al.: **Isolated proton bunch acceleration by a petawatt laser pulse**. *Nature Communications* 9(1), 423 (2018) DOI:10.1038/s41467-017-02663-1
- Döppner, T. ; Swift, D. C. ; Kritcher, A. L. ; et al.: **Absolute Equation-of-State Measurement for Polystyrene from 25 to 60 Mbar Using a Spherically Converging Shock Wave**. *Physical review letters* 121(2), 025001 (2018) DOI:10.1103/PhysRevLett.121.025001



## 2.4 Department Biophysics

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

Author: Prof. Ph.D. Marco Durante



Figure 10. Cave M at GSI in 1998 (left) and 2018 (right). Patients were treated until 2008 in cave M, while today the vault is only used for experimental research. As shown in the recent picture to the right, we saved the couch and the PET camera on top of the exit window for research applications. Photos by G. Otto/GSI.

In the Biophysics Department biological effects of accelerated heavy ions are studied with two main applications: cancer therapy and space radiation protection. In 2018, we celebrated the 20<sup>th</sup> anniversary of the start of carbon-ion therapy at GSI (Figure 10). In August and September 1998, the first patients were treated with a complete course of carbon therapy for a period of three weeks. It was a starting point of a success story that has led from fundamental research to a widespread medical application at GSI. Cancer therapy with heavy-ions at GSI was the result of joint research by the GSI Helmholtzzentrum, the Clinic of Radiology in Heidelberg, the German Cancer Research Center (DKFZ) in Heidelberg, and the Helmholtz research center in Dresden-Rossendorf (HZDR). Individual radiation treatment with heavy-ions had initially been conducted as early as December 1997. This had been preceded by four years of technical development of the therapy unit at the heavy-ion accelerator of GSI, which included a radiation facility for patients, and by 20 years of fundamental research in radiation biology and physics. In the period until 2008, GSI used carbon ion beams to treat more than 440 patients for tumours of the head and neck. The great success of the GSI pilot project has led to the construction of four heavy-ion treatment centres in Europe.

In [particle therapy](#), our Department collaborates with the clinical heavy ion centres in Heidelberg (HIT), Marburg (MIT), and Pavia (CNAO). In 2018 these collaborations have been substantially strengthened with several experiments carried out by our group at the Heidelberg and Marburg Ion Therapy Centres, and with the upgrade of the beam delivery system in Cave M in collaboration with CNAO in Italy.

In [space radiation protection](#) the Biophysics Department receives funding from the European Space Agency (ESA) to support the European program of space radiation research, so-called IBER. In 2017, ESA launched a call offering the possibility of beamtime at the GSI accelerators. 11 experimental groups from different European countries (Germany, Italy, Belgium and Romania) that have started their activities in 2018.

## Highlights in 2018

### Shielding in space

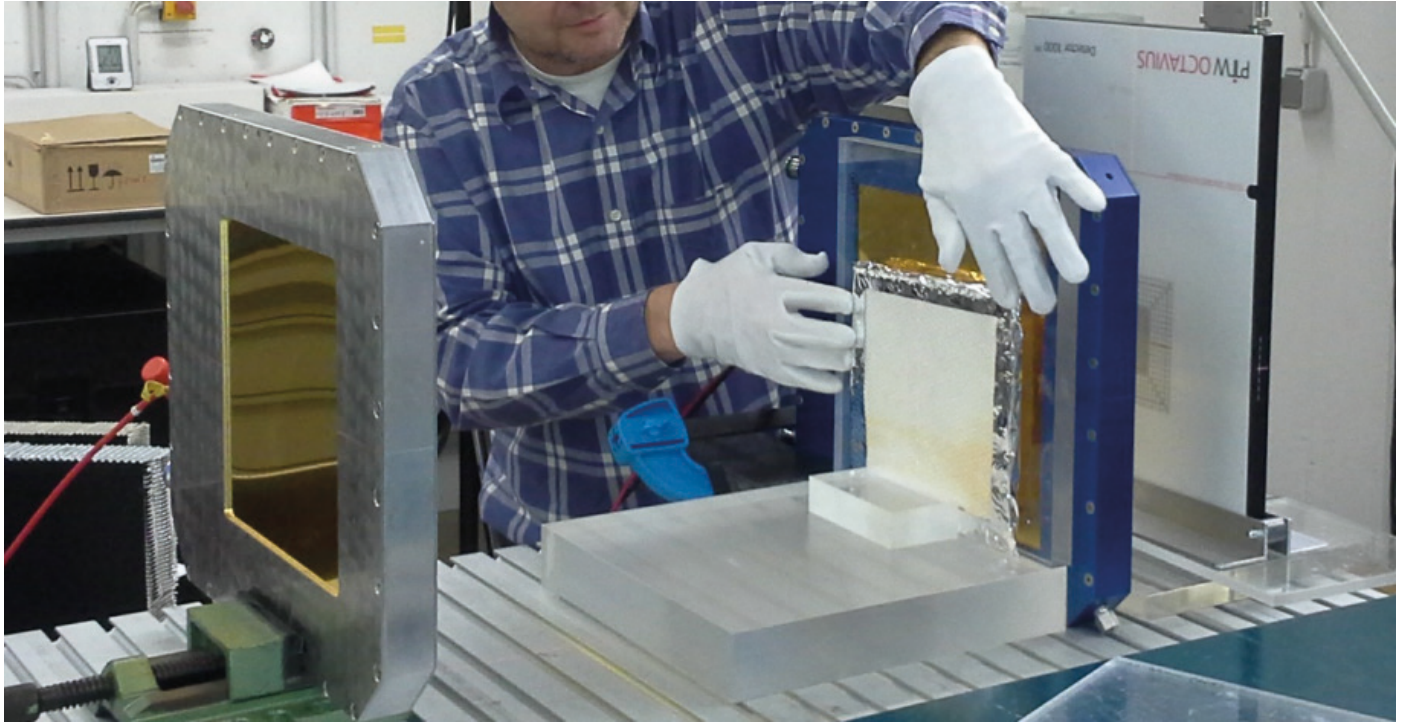


Figure 11. Installation of a block of lithium hydride for shielding experiments at GSI. Photo by U. Weber/GSI, license ccby4.

How can we protect the astronaut from radiation exposure during a mission to Mars? Passive shielding remains the only practical countermeasure to the radiotoxicity. How can we optimize the shielding? Results of a large experiment supported by ESA (Giraud et al., *Radiat. Res.* 2018 Aug. 20) point to new materials that may allow a safe trip to Mars. Researchers from the Biophysics group at GSI, in collaboration with NASA, INFN and Thales Alenia Space, measured the dose attenuation of high-energy heavy-ions in different materials, concluding that lithium hydride has the best performance on terms of dose reduction per unit shield mass (Figure 11). The discovery, supported by Monte Carlo simulations, paves the way to the implementation of safe shielding for interplanetary missions.

### Heavy ion-induced DNA damage

The biological effects of heavy-ions are a consequence of the DNA damage. It is generally acknowledged that heavy-ions produce clustered damages, more difficult to repair than the DNA double-strand breaks induced by X-rays. Using a combination of transmission electron microscopy and immunofluorescence, researchers from GSI in collaboration with the Saarland University in Homburg have visualized wide regions of chromatin decondensation in correspondence to clusters of DNA lesions produced by heavy-ions (Timm et al., *Radiother. Oncol.* 2018 Jul 23). These regions are repaired more slowly than isolated breaks, and may be responsible for the higher effectiveness of heavy-ions in therapy.



## Treating multiple targets with heavy-ions

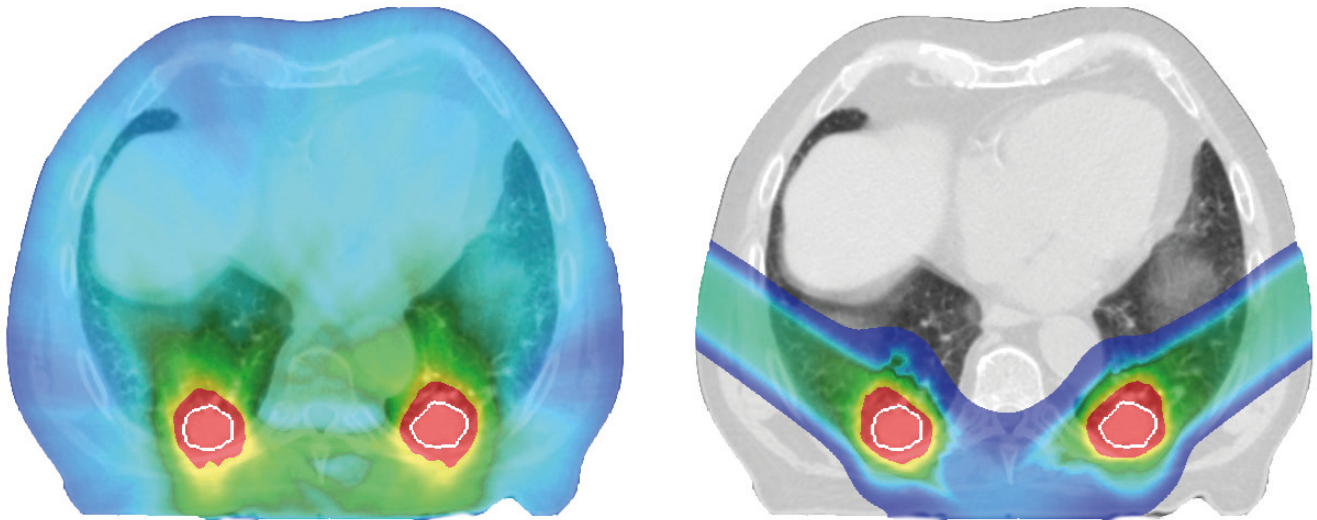


Figure 12. Simultaneous treatment of 2 separate lesions with X-rays (left) or carbon ions (right). The physical advantages of heavy ions lead to sparing of the normal tissue and to the possibility of applying high doses. Figure by K. Anderle, Ph.D. thesis, license ccby4.

Intensity-modulated particle therapy allows for highly conformal plans in motion and planning complexity in case of advanced lung cancer of patients with multiple lesions. We have now developed a system to optimize the plans in space and time for multiple tumours in the lung. We simulated the conformity of the plans on the different lesions and the sparing of the organs at risk with carbon ions and compared with stereotactic X-ray radiation as performed at the Champalimaud Foundation in Portugal (Anderle et al., *Phys. Med. Biol.* 2018 Jan 17). We showed that organs at risk receive a lower dose with heavy ions, and that a single treatment of 24 Gy can be done with carbon ions but not with X-rays, due to the proximity of organs at risk (Figure 12).

## Selected publications of 2018

- Anderle, K. ; Stroom, J. ; Vieira, S. ; et al.: **Treatment planning with intensity modulated particle therapy for multiple targets in stage IV non-small cell lung cancer.** *Physics in medicine and biology* 63(2), 025034 (2018) DOI:10.1088/1361-6560/aagc62
- Giraud, M. ; Schuy, C. ; Weber, U. ; et al.: **Accelerator-Based Tests of Shielding Effectiveness of Different Materials and Multilayers Fusing High-Energy Light and Heavy Ions.** *Radiation research*, RR15111.1 (2018) DOI:10.1667/RR15111.1
- Timm, S. ; Lorat, Y. ; Jakob, B. ; et al.: **Clustered DNA damage concentrated in particle trajectories causes persistent large-scale rearrangements in chromatin architecture.** *Radiotherapy and oncology* 129(3), 600 - 610 (2018) DOI:10.1016/j.radonc.2018.07.003



### 3. Research of the Hadron and Quark Matter (HQM) departments

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

Author: Prof. Dr. Joachim Stroth

The research activities of the past year were characterized by the recommissioning of the SIS18 and the start of the related FAIR Phase-0 Experiments on the one hand, and on the other hand by a long data taking during the run 2 campaign of the ALICE Collaboration before the second long-shutdown of LHC (LS2). In addition a new experimental area, suitable for experiments with high intensity ion beams, has been successfully inaugurated. It will be the home for the CBM test setup to commission free-streaming data taking in combination with first-level event selection based on full event reconstruction. The setup will comprise first-of-series or prototype detector modules of all sub systems. A direct fast data link to the central compute clusters installed in the Green IT Cube at GSI is already available. The operation of this prototype experiment is a key element to enable a fast start-up of the CBM detector system once the FAIR's SIS100 operation will provide first beam to the full experiment. As benchmark, fast  $\Lambda$  reconstruction is the focus of the setup.

In preparation of the experimental run addressing Ag+Ag reaction at maximum SIS18 beam energy, the HADES spectrometer has been substantially upgraded. A second mainframe has been installed behind the HADES spectrometer section and is now housing four sectors of the electromagnetic calorimeter. Two additional sectors will be completed until 2020. This new detector will enable reconstruction of light neutral mesons via their electromagnetic decays and also allow reconstruction of (radiative) baryonic (hyperon) decays. The second new sub-system is the RICH photon detector. In a joint project between CBM and HADES, a new, MAPMT based photon detector has been developed featuring an FPGA based digitization and read-out system solely relying on time measurements. A similar technology is also used for reading out the signals of the ECAL. This concept has been developed by the Experiment Electronic department in close collaboration with university groups. Both experiment runs were scheduled for 2018 but had to be shifted to 2019 due to an accident in the UNILAC.

The ALICE experiment has been up and running in 2018. While most of the time pp collisions were recorded, heavy-ions collisions could also be measured at the end-of-the-year campaign. The long pp run in particular allowed to record high statistics on rare events with high multiplicity. Such events are interesting since they show collective behaviour of the produced particles and also seem to feature deconfined matter. In parallel to data taking at CERN, the last production steps for the time projection chamber (TPC) upgrade were concluded. Part of the mass production was carried out in the large clean room of the GSI detector laboratory. In the two coming years the TPC will be prepared for high beamtime intensities with interaction rates up to 50 KHz. The key element to achieve this goal are read-out chambers operating without gating grid based on pad chambers with a four-stage amplification realized with gas-electron-multiplier foils (GEM'S).

A number of physic analysis projects have been pushed forward using synergies between the three HQM groups. Among these analysis projects are dileptons, hyper-nuclei production and fluctuation measurements of quantities related to conserved quantum numbers. The latter is in particular interesting since it is a promising observable for searching for landmarks in the QCD phase diagram like the critical point. The groups have put together their expertise rooting in both, fix-target and collider experiments, to develop strategies to correct the raw-data for a number of detector and experimental effects.



### 3.1 Department HADES at GSI

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

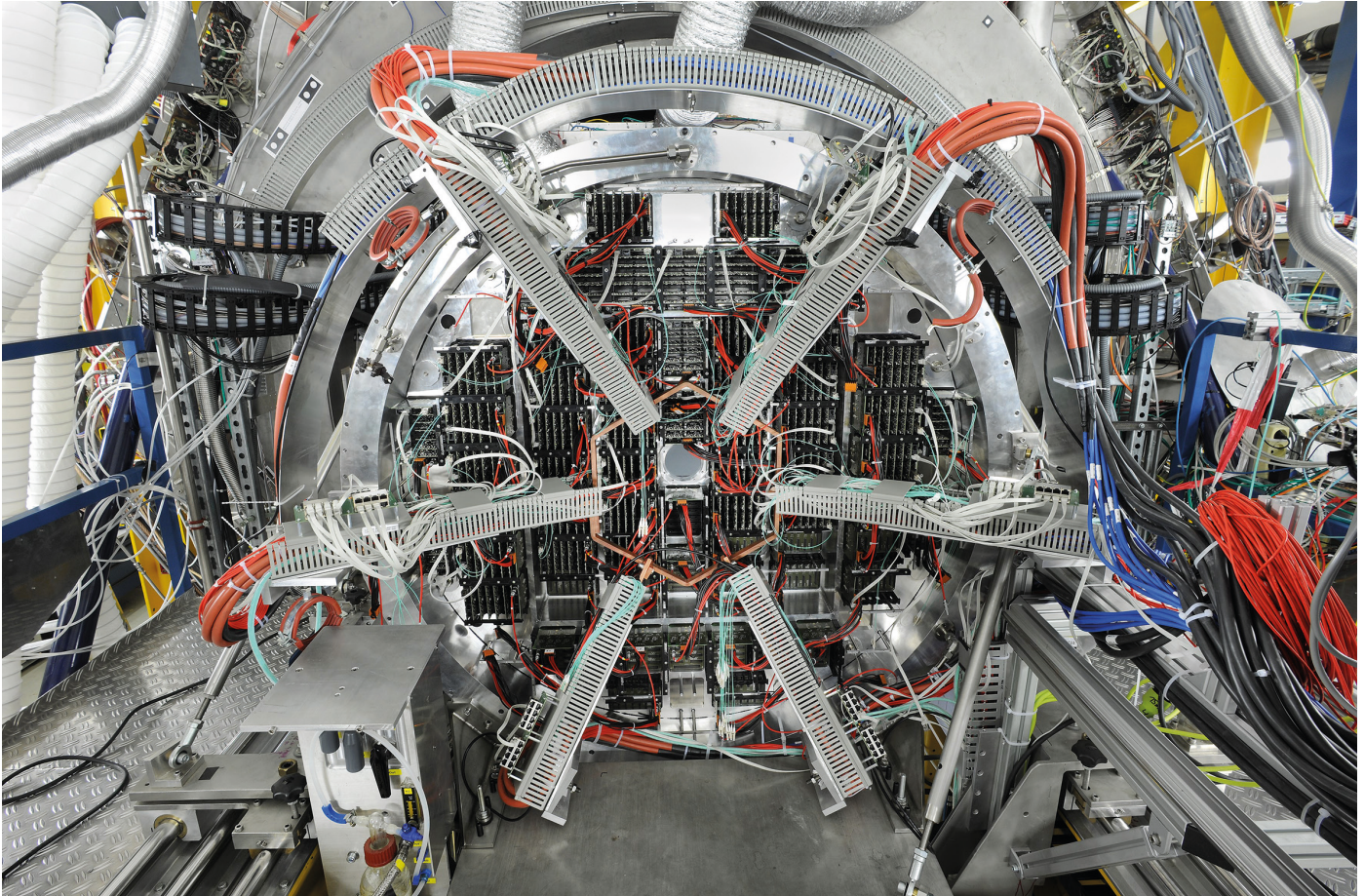


Figure 13. Photograph of the upgraded HADES detector. View from the front, in direction of the beam, onto the backplane of the new RICH photo detector. In total 1011 FPGA's, distributed over 74 printed circuit boards digitize the analogue information and prepare the data for readout over glas fiber links. The photo sensitive area is composed of 428 multi-anode PMT's each providing 64 individual PMT cells.

During 2018 the HADES activities have concentrated, on the one hand, on finalizing the analysis of the data taken during the 2012 Au+Au run and, on the other hand, on upgrading the experimental setup: adding an electromagnetic calorimeter behind HADES, replacing the RICH photon detector by a more efficient one, preparing the installation of a new straw-tube forward detector, and making various smaller improvements.

An important number of results have been obtained and already published or submitted for publication. One of these papers, i.e. "Probing dense baryonic matter with virtual photons" by J. Adamczewski-Musch et al., accepted in Nature Physics, reports the observation of thermal dilepton radiation measured for the collision system Au+Au at 1.23 A GeV. For the first time such radiation could be observed for baryon-dominated matter. The spectral distribution is in essence falling off exponentially and therefore supports the assumption of a strong broadening of the  $\rho$  meson in hot and dense matter. The publication also discusses possible links of this observation to a partial restoration of the spontaneously broken chiral symmetry. One direct consequence of such a strong broadening is the opportunity to extract the mean source temperature in a model independent way to be  $T=70$  MeV. This is the second direct measurement of a fireball

temperature after the success of the NA60 collaboration at the CERN SPS. The outlook emphasizes the bright opportunities of upcoming experiments at FAIR and NICA to continue such measurements in a very systematic manner. Moreover, the connection of such measurements with the findings from observing neutron star mergers is outlined.

### Other HADES physics publications from 2018 are:

- Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al.: **Deep sub-threshold  $\phi$  production in Au+Au collisions.** *Physics letters / B* 778, 403 - 407 (2018) DOI:10.1016/j.physletb.2018.01.048
- Adamczewski-Musch, J. ; Agakishiev, G. ; Arnold, O. ; et al.:  **$\Sigma^0$  production in proton nucleus collisions near threshold.** *Physics letters / B* 781, S0370269318301539 (2018) DOI:10.1016/j.physletb.2018.02.043
- Adamczewski-Musch, J. ; Arnold, O. ; Behnke, C. ; et al.: **Centrality determination of Au + Au collisions at 1.23A GeV with HADES.** *The European physical journal / A* 54(5), 85 (2018) DOI:10.1140/epja/i2018-12513-7

The upgraded HADES setup has been commissioned with a silver beam delivered by SIS18 during a one-week engineering run in December 2018. Both newly installed detector systems worked very well. The replaced RICH photodetector is expected to provide a lepton pair reconstruction efficiency of at least a factor two better than realized with the old gas filled pad chambers in the 2012 Au+Au run. The added electromagnetic lead glass calorimeter (ECAL) will also augment electron and positron reconstruction by providing particular shower signals in the lead glass. Such information was before provided by a sampling calorimeter (PreSHOWER) now taken out of the set-up after almost 15 years of successful operation.

### Outlook for 2019

In the second half of 2019, the spectrometer will be further complemented by a forward detection system to improve performance for the reconstruction of exclusive reaction channels. The respective tracking stations are based on PANDA technology and are realized in close collaboration with PANDA. Experiments on hyperon production on p+p collisions, planned for the coming years and focusing on the reconstruction of electromagnetic transition form factors, are flagged PANDA Phase-0 activities at GSI. Other runs anticipated for the coming years are dedicated to experiments with secondary pion beams. Also foreseen is a revision of the data acquisition system. This concerns the replacement of first-generation FPGA boards, implementation of new firmware and new front-end electronics for the MDC drift chamber system. The expected result is to boost the data taking rate of HADES to 200 kHz in p+p and  $\pi$ +p collision experiments.



## 3.2 Department CBM at FAIR

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

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 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 and vector mesons. These measurements will be performed at reaction rates up to 10 MHz.

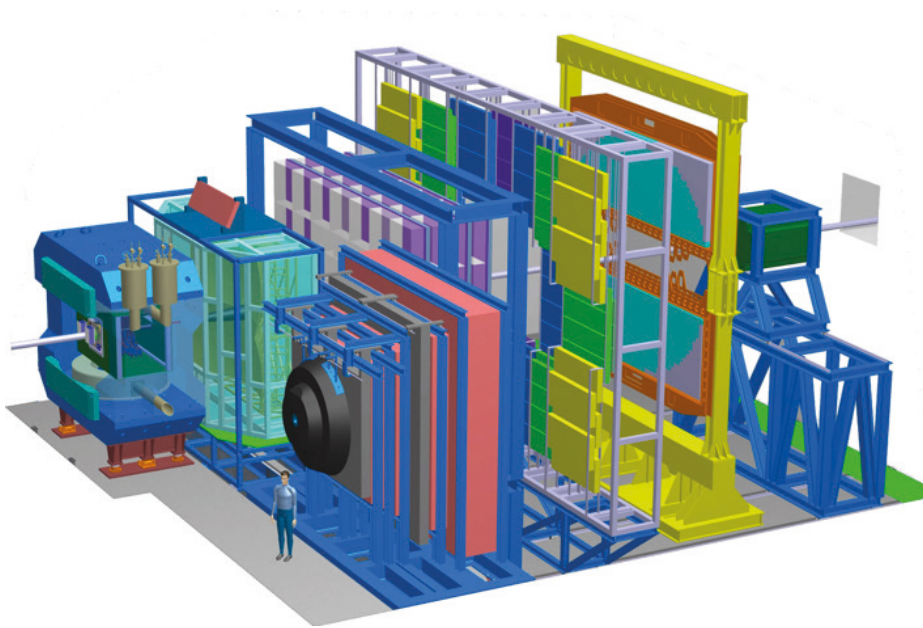


Figure 14. The CBM experimental setup. The CBM components are described in the text. For muon measurements, the RICH will be exchanged by the MuCh which is shown in a parking position to the right of the beam axis.

The planned CBM experimental setup is depicted Figure 14 and includes the following components:

- 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 micro pat-

tern 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) computing system for online event reconstruction and selection.

Apart from collaboration tasks, the CBM department at GSI is responsible for the design, development and construction of the Silicon Tracking System STS, development of the front-end electronics for the time-of-flight detector, the layout of the cave at FAIR and its infrastructure, and for software development and feasibility and performance studies.

### mCBM commissioning started

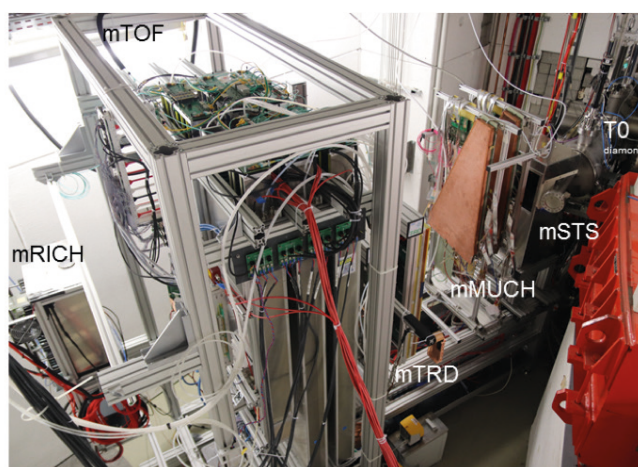


Figure 15. mCBM setup featuring a “slice” of the future CBM experiment. The beam from the SIS18 enters from the right, where it hits a 10% X/X<sub>0</sub> target producing secondaries at rates comparable to the envisioned rates at CBM.

The primary aim of the CBM full-system test-setup mCBM@SIS18 (“mini-CBM”), comprising final prototypes of all CBM detector subsystems, is to study, commission and test the detector systems with the free-streaming data acquisition and the fast online event reconstruction and selection under realistic experiment conditions. The construction of the mCBM cave (HTD) including the experiment infrastructure has been completed. Optical fibers connect the mCBM setup with the mCBM DAQ container and furthermore with the Green IT Cube hosting the input and processing nodes for online reconstruction and selection. The fast data transport into the Green IT Cube has been tested successfully. Two stations of the mTRD subsystem as well as the mTOF have been mounted (see Figure 15). The commissioning of the individual free-streaming read-out systems is ongoing. In November the first mSTS station and two mMUON stations have been integrated.

A first successful commissioning with beam of the CBM full-system test-setup mCBM@SIS18 comprising final prototypes of all CBM detector subsystems including its ultra-fast, free-streaming read-out and data transport into the a high performance computer farm inside the GreenITCube, has started during the machine engineering runs in December 2018. The main commissioning beam time took place in March 2019 using Ag (45+) beam with incident kinetic energy of 1.58 GeV per nucleon and beam intensities up to 10<sup>8</sup> Ag ions per second leading to 10 MHz collision rates. As detector subsystems, one station of the silicon tracking system (mSTS), two GEM modules of the muon system (mMUON), 2x stations of the mTRD detector (mTRD), five RPC modules of the TOF wall (mTOF) as well as a first RICH test system (mRICH) has been mounted (see photography in Figure 15, beam enters to the right). Inside the target chamber a fast and radiation-hard diamond T<sub>0</sub> counter has been installed providing the reaction start time (T<sub>0</sub>) for the time-of-flight measurement. Data rates up to 2.5 GB per second have been observed by the processing nodes inside the GreenITCube during data taking. First results show clean correlations between the synchronized data streams of the detector subsystems demonstrating a first conceptual proof.

## The Silicon Tracking System

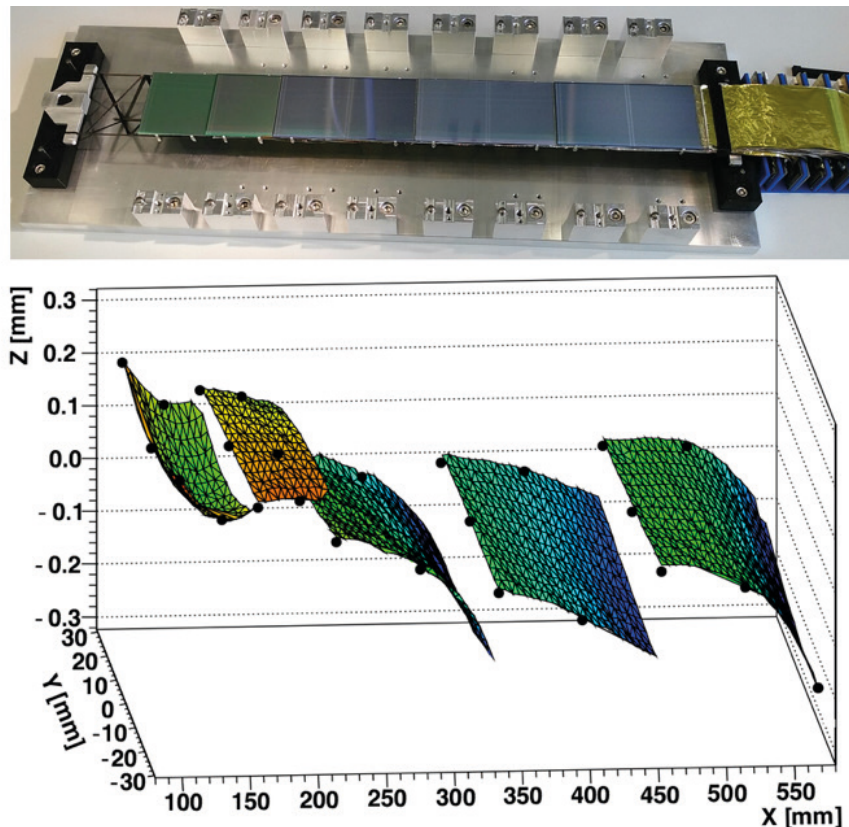


Figure 16. Top: Assembly of 5 modules on a carbon fiber ladder. Bottom: Measurement of the sensor surface space points with a step size of 5 mm in both directions. The black dots refer to the alignment marks on the sensor.

The Silicon Tracking System (STS) will be the key detector of the CBM experiment. It will be built by the GSI-CBM department together with the Detector Laboratory in close collaboration with German university groups (Tübingen), KIT Karlsruhe and groups from Russia (JINR), Ukraine (KINR), and Poland (WUT, AGH). Over the past year(s) procedures for modules and ladder assembly, as well as procedures for quality assurance have been developed [E. Lavrik et.al, NIM A 922 (2019), DOI:10.1016/j.nima.2018.10.210, E. Lavrik et al., NIM A 935 (2019), DOI: 10.1016/j.nima.2019.04.039]. The order for the sensor has been submitted and thus the transition from R&D and pre-series production will be by the end of 2019. The Figure 16 shows an assembled ladder consisting of 5 sensors with readout cables, i.e, modules on its assembly jig. On the bottom figure the metrology of the sensors after mounting onto the ladder is shown revealing an assembly precision below 100  $\mu\text{m}$ , which is within specs.



### 3.3 Department ALICE at CERN LHC

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

Author: Dr. Kai Schweda; Prof. Dr. Silvia Masciocchi

The Quark-Gluon Plasma (QGP) is the state of de-confined and thermalized strongly interacting matter produced in high-energy nucleus-nucleus collisions. Its detailed characterization is a major long-term goal of the ALICE experiment at CERN using proton-proton, proton-lead and lead-lead collisions at unprecedented high energies provided by the Large Hadron Collider.

#### Highlights in 2018

The second long data taking period at LHC extended from 2015 to 2018 and culminated with four weeks of lead-lead collisions in November/December 2018 at a center-of-mass energy of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV at a collision rate of up to  $8000 \text{ s}^{-1}$ . The targeted integrated luminosity of  $1 \text{ nb}^{-1}$  was successfully recorded by ALICE. This significantly enhances the ALICE data set to a factor of nine for the most central collisions where highest energy densities and temperatures are reached. The Time Projection Chamber (TPC) is the main ALICE detector for particle tracking and identification. The GSI-ALICE team is responsible for its operation and calibration. We achieved an optimum data quality in terms of detector performance: local but unexpectedly large spatial distortions in the reconstruction of charged-particle trajectories due to accumulating space charge in the TPC were mitigated by a factor ten or more by means of optimized potential settings at the readout chambers. The readout chambers were at an amplification gain that is approaching to the saturation regime with an energy resolution that is close to the theoretical limit. Still, no high-voltage trips occurred at these extreme interaction rates resulting in a homogeneous acceptance over the entire data taking period with lead-lead collisions. The new data set is now fully calibrated and reconstructed, so that all data is ready for physics analysis.

Heavy quarks such as charm and beauty are, due to their large mass, unique probes into the study of QGP properties. The GSI-ALICE team is substantially contributing to the analysis on the production of the  $J/\psi$  meson, a bound state of a charm and an anti-charm quark. Work on the reconstruction of the decay topologies of charmed baryons has successfully started.

The production mechanism of light nuclei such as deuteron, helium-3 and helium-4 is still poorly understood. At LHC energies, their corresponding anti-particles are produced in similar amounts. This allows for sensitive tests of fundamental symmetries, e.g. through the measurement of the mass difference between helium-4 and anti-helium-4. The loosely bound hyper-triton, a bound state of a deuteron and a lambda-hyperon, is of similar size as the whole collision system. Its lifetime appears to be shorter than the lifetime of the free lambda-hyperon, which remains a puzzle. Our group is deeply involved in these analyses, amongst others.

The ALICE TPC is presently being upgraded with new readout chambers based on Gas Electron Multiplier (GEM) technology. Starting in 2021, ALICE will record lead-lead collisions at an unprecedented interaction rate of 50 kHz in continuous readout mode. The GSI-ALICE team took the responsibility for the GEM foil testing and framing, and for the assembly of the outer, thus larger in size, readout chambers. The latter comprises the chamber aluminium body and pad backplane that were prepared at the Universities of Frankfurt and Heidelberg and three stacks of four GEM foils each. After the assembly, the chambers were extensively tested at GSI, in order to assure that each one meets the stringent quality criteria regarding gain uniformity and resolution on the energy deposit measurement. All 20 chambers were delivered to CERN on schedule. This work was performed in close collaboration with the GSI detector laboratory taking advantage of the excellent conditions in the clean room.

## Outlook for 2019

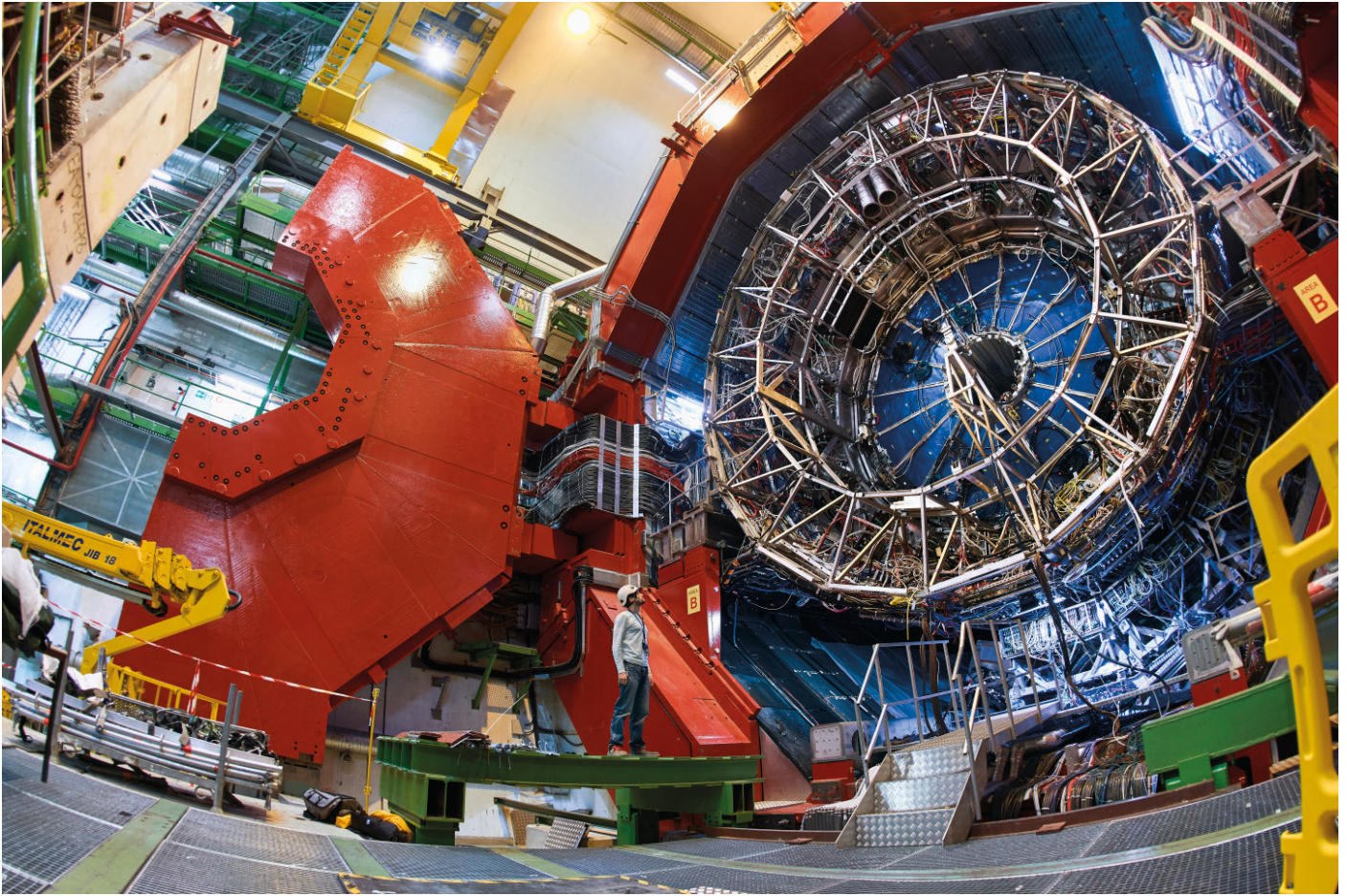


Figure 17. The ALICE TPC shortly before being moved to the surface after 4435 days underground. Photograph: Julien Ordan, source: CERN.

On December 3, 2018, the ALICE magnet was opened and the entire infrastructure in front of it was then removed, see Figure 17. The TPC was extracted from the ALICE mainframe and brought to the surface on March 4. It is now residing in a class ISO 6 clean-room of a neighbouring building.

## Selected publications of 2018

- Acharya, S. ; Torales - Acosta, F. ; Adamova, D. ; et al.: **Measurements of low-pT electrons from semileptonic heavy-flavour hadron decays at mid-rapidity in pp and Pb-Pb collisions at  $\sqrt{s_{NN}}=2.76$  TeV.** *Journal of high energy physics* 2018(10), 61 (2018) DOI:10.1007/JHEP10(2018)061
- Acharya, S. ; Torales - Acosta, F. ; Adamova, D. ; et al.: **Energy dependence and fluctuations of anisotropic flow in Pb-Pb collisions at  $\sqrt{s_{NN}}=5.02$  and 2.76 TeV.** *Journal of high energy physics* 2018(7), 103 (2018) DOI:10.1007/JHEP07(2018)103



## 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. Its main research instruments and experimental areas at GSI/FAIR 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 are integral part of the NUSTAR Collaboration and participate in and contribute, often in a leading position, to experiments with exotic nuclei at GSI-FAIR and other facilities (e.g. GANIL, JYFL, RIKEN, JAEA Tokai, ANU Canberra). This assures important new scientific results, maintaining skills, expertise and capability, constant training and education of next-generation scientists. This is particularly important to continue superheavy element research at GSI and prepare the collaboration for NUSTAR members' experiments at FAIR.

A major activity in year 2018 was the preparation of the FAIR project evaluation, where the updated NUSTAR science case was reviewed. A document, comprising the project status and scientific goals of NUSTAR at FAIR, was prepared by the NUSTAR Board of Representatives in close cooperation with the NUSTAR Collaboration Committee. The planned research programme will allow for world-wide unique experiments on important and challenging scientific questions even in year 2025 and far beyond. Presently, the NUSTAR Collaboration has more than 800 registered members from more than 100 institutions in 39 countries.

At the NUSTAR Annual Meetings and during the NUSTAR Weeks, the various NUSTAR sub-collaborations presented their views and plans on the FAIR Phase-0 Program. This has already started with first experiments at the UNILAC for the superheavy element program and some stable-beam experiments at R<sup>3</sup>B, and is expected to start fully in year 2020 with several beamtimes at SIS-18. 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 PhD students and young post-docs 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) or at other facilities (e.g. AGATA at GANIL, new setups of MATS and LASPEC at TRIGA in Mainz). The NUSTAR strategy for the coming decade aims at the exploitation of new opportunities and a continuous transition from GSI to FAIR as soon as the Super-FRS becomes available.

## 4.1 Department FRS/SFRS

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

In 2018 the activities of the FRS/SFRS group concentrated on the preparation of the FRS for the approved NUSTAR experiments at SIS18 in FAIR Phase-0 and on the preparation of high-resolution spectrometer experiments with the Super-FRS/FRS and development of related setups. Intense work force was devoted to the commissioning of the FRS and all its sub-systems after the long shut-down (since August 2016), the development and implementation of new control and monitor software in the framework of the FAIR LSA-based software environment, and the coordination of the FRS dipole magnet repair. Several FAIR TDRs have been completed and an in-kind contract for the helium recovery unit of the cryogenic stopping cell (CSC) for the low-energy branch (LEB) of Super-FRS was signed. Tel Aviv University from Israel joined the Super-FRS Experiment Collaboration and as such Israel is a new partner country. Also, new collaborations were started with RIKEN, Tokai and MSU on deep inelastic reactions (for new-isotope production studies, ground-state studies, etc.), in particular multiple nucleon transfer experiments with stable beams and exotic nuclei at Super-FRS/FRS.

### Highlights in 2018

The scientific activities of the department build on the use of the Super-FRS/FRS as high-resolution separator/spectrometer with a variety of ion-optical modes and several major detection systems at its main focal planes. Here, we concentrate on the Ion Catcher, WASA and EXPERT, and ion-optics.

#### Ion Catcher

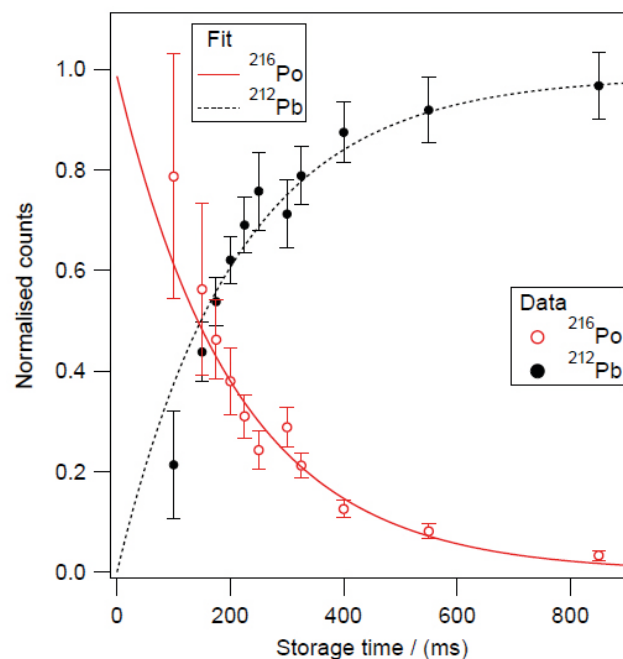


Figure 18.  $^{216}\text{Po}$  and  $^{212}\text{Pb}$  counts, normalized to their sum, as a function of CSC storage time up to about one second. The lines represent a global fit, from which the lifetimes are extracted.

The FRS Ion Catcher is the prototype, development platform and test bench for the cryogenic stopping cell (CSC) at the Low-Energy Branch of the Super-FRS. The pilot experiments of the Super-FRS Exper-



iment Collaboration such as ground-state measurements of exotic nuclei and deep inelastic reaction studies with primary and secondary beams are carried out at the FRS. The areal weight of the stopping gas has been increased by a factor of about two to 10 mg/cm<sup>2</sup> by several technical upgrade measures and a carbon-cluster laser ablation ion source and mass filter unit has been installed in order to provide suitable calibrant ions over the complete mass range of relevance. Furthermore, a novel concept for simultaneous measurement of masses, Q-values, isomer excitation energies, half-lives and decay branching ratios of exotic nuclei has been demonstrated. The method is based on the use of the stopping cell as an ion trap, combining the storage of mother and daughter nuclides for variable durations, and afterwards the identification and counting of them by the multiple reflection time-of-flight mass spectrometer (MR-TOF-MS). The method was utilized to record different decay modes and was proven to yield half-lives consistent with literature values. Figure 18 shows the decay and growth of <sup>216</sup>Po  $\alpha$ -decaying into <sup>212</sup>Pb and the corresponding curves fitted to the experimental data, from which a half-life of  $T_{1/2}=145\pm 11$  ms is determined (literature value is  $145\pm 2$  ms [G.Audi et al., Chinese Phys. C41, 030001, 2017]). The results open the door for the measurement of branching ratios of exotic nuclei with multiple decay channels.

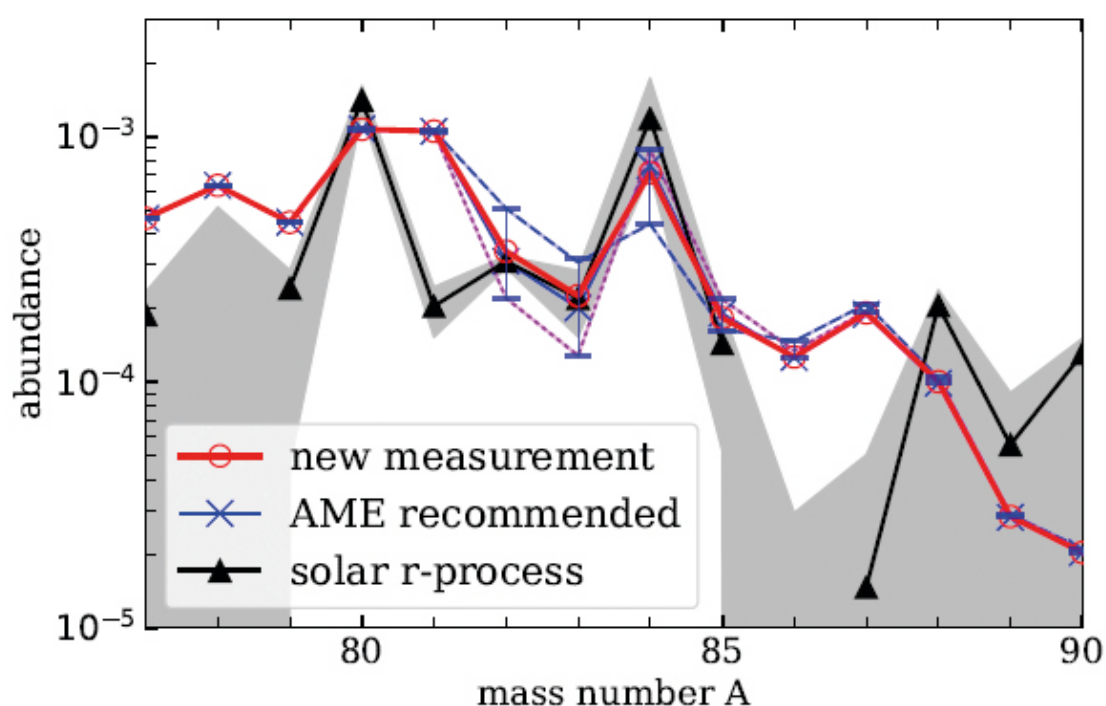


Figure 19. Final abundance for astrophysical conditions of blue kilonovae observations following the GW170817 binary neutron star merger. The first mass measurements on <sup>84,86</sup>Ga accomplished with the MR-TOF-MS of TITAN strongly reduce the uncertainty at the A~84 characteristic peak of the r-process abundances and constrain the nuclear properties for <sup>82</sup>Se, an isotope that can only be produced via the r-process. For details see <https://arxiv.org/abs/1810.11561>

The group has contributed to the implementation of and experiments with its newly constructed Multiple-Reflection Time-Of-Flight Mass Spectrometer/Separator (MR-TOF-MS/S) at the Ion Trap for Atomic and Nuclear Science at TRIUMF, TITAN. The MR-TOF is used twofold, as mass separator and simultaneously as mass spectrometer. This dual capability of the same device becomes possible due to the original concept of mass-selective re-trapping of ions after mass separation. Mass-selective re-trapping, developed and tested at GSI and JLU-Gießen, was used for the first time in an online experiment with radioactive beams; it enabled the measurement of many atomic masses for the first time. The instrument is also well-suited for efficient use for beam diagnosis, identification and the development of new beams at the Isotope Separator and Accelerator ISAC. Thus, the MR-TOF-MS became the work horse of the TITAN experiment in year 2018 and led to several publications [e.g. E. Leistenschneider et al., Phys. Rev. Lett. 120(6), 062503 (2018); M.P. Reiter et al., Phys. Rev. C98(2), 024310 (2018)] and new astrophysical findings, as shown in Figure 19.

## EXPERT

The construction of the “Exotic Particle Emission and Radioactivity by Tracking for the Super-FRS Experiment” (EXPERT) is underway while the analysis of previous pilot experiments at FRS continues and simulation codes are developed for FAIR experiments. With EXPERT detectors located at the central and final focal plane of FRS or Super-FRS, decays of dripline nuclei and unbound systems are studied by measuring the trajectories of their decay products in-flight via a tracking technique with microstrip detectors and by optical time projection chambers (O-TPC).

For the upcoming FAIR Phase-0 Experiments S443/S459, two options of read-out electronics and DAQ have been tested for the DSSD (double-sided Si micro-strip detectors for tracking of the in-flight decay products): (i) the SIDEREM modules with the MBS DAQ (Data Acquisition of GSI development) and (ii) the AMS (Alpha Magnetic Spectrometer) system with AMS DAQ. It turned out that the AMS system yields less noisy spectra. Two 64-strip silicon detectors with an active area of 6x6 cm<sup>2</sup>, which are needed for the Time-of-Flight (ToF) measurement, have been produced by the collaborators from the Ioffe Institute (St. Petersburg) and JINR (Dubna). The so-called TAMEX2 (a GSI experiment developed by the electronic laboratory) front-end electronics will be used for the ToF Si detectors and for providing the trigger signals. The synchronization of the AMS system with the timing TAMEX2 sub-system within the master MBS DAQ has been implemented [M.Bajzek, GSI summer student program 2018]. The newly-developed fast-timing front-end electronics (128-channels) for the ToF silicon detectors has been tested with the Ar, Ag primary beams from SIS18 during the R<sup>3</sup>B setup tests. Therefore all detectors needed in approved proposals S443/S459 have been tested and are ready for the experiments. The Go4 code for on-line analysis has been prepared.

The recently analyzed results of previous EXPERT pilot experiments have been published in Refs. [X.-D. Xu et al. Phys. Rev. C 97, 034305 (2018); I. Mukha et al., Phys. Rev. C 98, 064308 (2018); L.V. Grigorenko et al., Phys. Rev. C 98, 064309 (2018)]. Among other findings, the discovery and first spectroscopy results of the previously unknown isotopes <sup>29,30</sup>Ar and <sup>28,30</sup>Cl are reported. On this basis, predictions of the very last isotopes in the proton-rich edge of argon and chlorine chains have been obtained. This is a significant advance in establishing the limits of existence of nuclei in the nuclear landscape as well as in approaching the transition region to chaotic nuclear systems resp. amorphous nucleon matter.

As a step towards forthcoming experiments and more detailed analysis, Monte-Carlo simulations have been started where the correlations between the decay products (heavy-ions and proton(s)) are analyzed taking into account both, the transverse momentum (emission angles) and the longitudinal momentum, yielding more refined decay results when the second half of the (Super-)FRS is used as high-resolution spectrometer.

## WASA

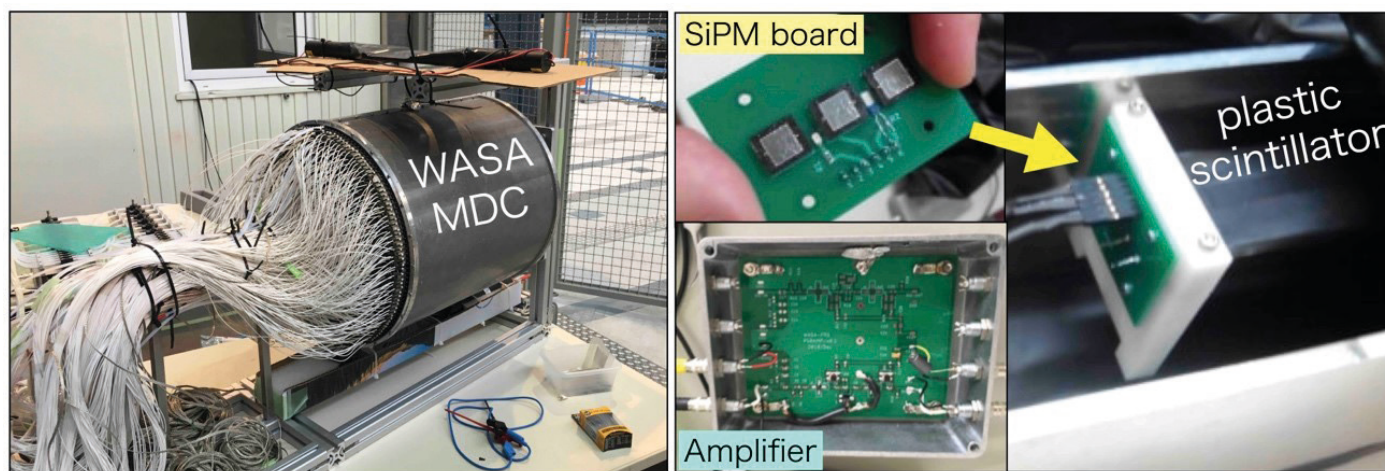


Figure 20. The central tracking detector (WASA-MDC) tested at GSI (left) and the newly-developed prototype of the plastic scintillator barrel (WASA-PSB) with SiPM readout (right).

The preparations for new experiments using WASA@FRS have started and several development branches are underway. The experiments planned in FAIR Phase-0 aim at high-resolution spectroscopy to produce and study hypernuclei [T.R.Saito et al., Experimental proposal to GPAC, S447 (2017)], mesic nuclei [K.Itahashi et al., Experimental proposal to GPAC, S457 (2017); Y.K.Tanaka et al., Phys. Rev. C 97, 015202, (2018)] and nucleon resonances in exotic nuclei. In 2018, there were significant achievements towards the realization of these challenging experiments. Firstly, the central tracking detector (WASA-MDC) has been re-assembled and tested at GSI (Figure 20, left). The data acquisition system has been renewed and adapted to the GSI-standard MBS system. Secondly, a prototype of the new plastic scintillator barrel (WASA-PSB) with SiPM readout has been developed aiming at a better time resolution (Figure 20, right). By testing the prototype with a  $^{90}\text{Sr}$   $\beta$ -source, time resolution of  $\sim 80$  ps was achieved, which fulfills the experimental requirements [R.Sekiya, GSI summer student program 2018]. Finally, the transportation of the WASA super-conducting solenoid magnet and CsI calorimeter from FZ-Jülich to GSI has been prepared.

## Ion optics

Ion-optical developments are a key competence of the department and these have progressed continuously: a) new ion-optical settings of the FRS have been developed to obtain increased rates of exotic nuclei for the benefit of the whole NUSTAR Collaboration; this is accomplished through thick targets and an adapted high optical transmission; b) a new mode for high-resolution momentum measurements and a high-transmission mode for exotic isotopes spatially separated and energy bunched with achromatic and monoenergetic degraders has been designed; c) in collaboration with the BigRIPS team at RIKEN Nishina center and in preparation of Super-FRS experiments, i.e. experiments at a two-stage in-flight separator (consisting of pre- and main-separator), several new modes have been developed, which allow for increased spatial separation (beneficial for heavy elements), substantially reduced background and which couple two independent, subsequent achromatic systems (like Super-FRS and the Low-Energy Buncher/Spectrometer). Besides the general benefit for many NUSTAR experiments, these ion-optical developments are a base for a new category of experiments exploring e.g. exotic hypernuclei and mesic atoms, which are pursued by the Super-FRS Experiment Collaboration.

To ensure the integration of the FRS in the new LSA control system framework for FAIR, and in preparation of the Super-FRS control, a so-called "machine model" was developed and tested, which will allow the reliable operation of the FRS, especially fail-safe with respect to the expected increased SIS-18 beam intensities.

## Outlook for 2019

The main activities of the group will be:

- a) the implementation of the remote-handling system for all components of the FRS target area;
- b) the coordination of the ongoing repair work of the FRS dipole magnets;
- c) the re-commissioning of the FRS with the new, LSA-based control system of FAIR and all related software developments and tests; this will be pursued continuously without and with beam and includes the operation of the FRS standard equipment (all elements needed for production of exotic nuclei, their separation and identification) and its electronics and data-acquisition and analysis systems; this also includes training of the NUSTAR Beam Team, preparation of settings and detector tests for the approved experiments scheduled for 2020, ion-optical developments and tests of components for the Super-FRS at FAIR; continuous improvement of computing codes for experiment simulations, e.g. codes for ion-optics, nuclear and atomic interaction, and implementation of heavy-ion specific subroutines in GEANT4;
- d) the preparation of all approved experiments of the Super-FRS Experiment Collaboration and contributions to the construction of related detector systems (like EXPERT, WASA, Ion Catcher etc.) for experiments at Super-FRS at FAIR Phase-Day-1.

## Selected publications of 2018

- Leistenschneider, E. ; Reiter, M. P. ; Ayet San Andrés, S. ; et al.: **Dawning of the N = 32 Shell Closure Seen through Precision Mass Measurements of Neutron-Rich Titanium Isotopes.** *Physical review letters* 120(6), 062503 (2018) DOI:10.1103/PhysRevLett.120.062503
- Tanaka, Y. K. ; Itahashi, K. ; Fujioka, H. ; et al.: **Missing-mass spectroscopy of the  $^{12}\text{C}(\text{p}, \text{d})$  reaction near the  $\eta'$ -meson production threshold.** *Physical review / C* 97(1), 015202 (2018) DOI:10.1103/PhysRevC.97.015202
- Xu, X.-D. ; Mukha, I. ; Grigorenko, L. V. ; et al.: **Spectroscopy of excited states of unbound nuclei  $^{30}\text{Ar}$  and  $^{29}\text{Cl}$ .** *Physical review / C* 97(3), 034305 (2018) DOI:10.1103/PhysRevC.97.034305



## 4.2 Department Nuclear Reactions

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

### Activities in 2018

The preparation of the R<sup>3</sup>B setup for the first FAIR Phase-0 production beam time in 2019 was in the focus of the activities in 2018. The former R<sup>3</sup>B-LAND experiment in Cave C has been fully rebuilt based on the new R<sup>3</sup>B equipment including the new super-conducting dipole magnet GLAD, as well as substantial fractions of the new detections systems developed and constructed for R<sup>3</sup>B at FAIR. The installation of GLAD was finalized. After cool-down, the magnet has been trained and has seen its full magnetic field. Construction and test of a completely new heavy-ion tracking system has been finalized, including among others several large-area scintillating-fiber detectors, a high-resolution ToF wall, as well as silicon detectors, all with their respective readout electronics. The new DAQ system of R<sup>3</sup>B runs with an-order-of-magnitude increased trigger rate of 10 kHz. 10 double planes of the new neutron detector NeuLAND, which will comprise 30 double planes when completed, have been installed and prepared for measurements. The calorimeter CALIFA for gamma and light charged-particle detection has been installed in its demonstrator version with a dedicated mechanical structure.

The systems have been tested with parasitic beams during the SIS engineering runs. The present setup thus will meet already now several of the design goals of the final R<sup>3</sup>B experiment. These are improved mass resolution due to the combination of GLAD and the new tracking system, higher resolution for neutrons and gamma rays, provided by NeuLAND and CALIFA, respectively, as well as an overall higher rate capability.

### Scientific Highlights in 2018

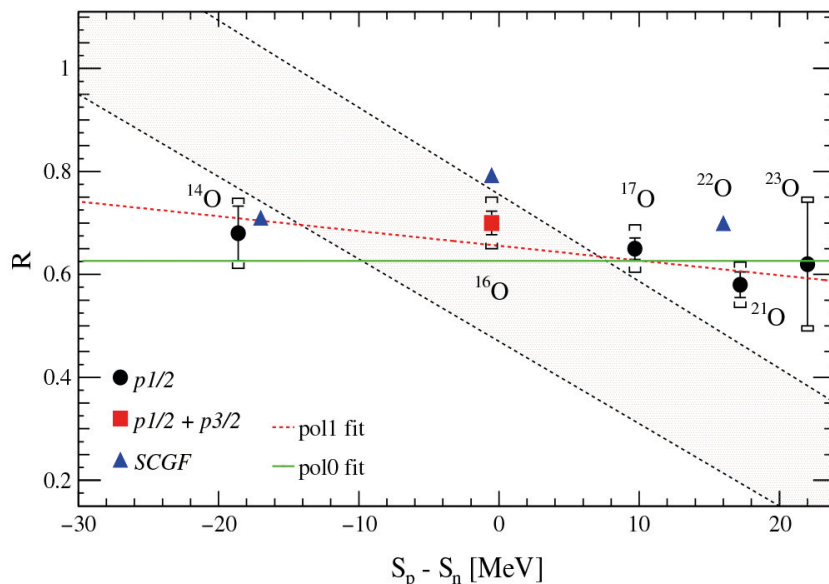


Figure 21. Reduction of spectroscopic factors as a function of neutron-proton asymmetry given in terms of the difference in nucleon binding energies  $S_p - S_n$ . Symbols represent results from the present experiment [1], while the grey shaded area indicates the trend deduced from nucleon removal reactions.

The kinematically complete measurement of proton-induced quasi-free scattering in inverse kinematics has been pioneered and established with a <sup>12</sup>C benchmark experiment by us few years ago. This new

technique has been applied with radioactive beams to investigate a long-standing puzzle. We know from electron-induced knockout reactions that the single-particle strength in nuclei is reduced to around 60–70% compared to mean-field models like the shell model, caused by correlations not included in a shell model like coupling to collective states and short-range correlations (SRC). From a systematic study of one-nucleon-removal reactions from radioactive beams at intermediate energy around 100 MeV/u it has been concluded (J.A. Tostevin and A. Gade, PRC 90 (2014) 057602) that this reduction strongly depends on neutron-proton asymmetry, as indicated in Figure 21 by the grey shaded diagonal band. Such a trend could be caused by stronger fragmentation of the single-particle strength for more deeply bound valence nucleons in asymmetric nuclei, or, by a stronger effect of SRC. The latter could be related to the  $n$ - $p$  dominance of SRC pairs, as recently reported from an experiment at JLAB (M. Duer et al., NATURE 560 (2018) 617).

R<sup>3</sup>B measured cross sections for the  $(p,2p)$  quasi-free knockout reactions for 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  $R$  around 0.6 to 0.7 (see Figure 22). The R<sup>3</sup>B data show no, or only a weak asymmetry dependence. The results indicate that the trend deduced from nucleon-removal reactions at energies around 100 MeV/u might be related to a not fully understood reaction mechanism of the nucleon removal at lower beam energies.

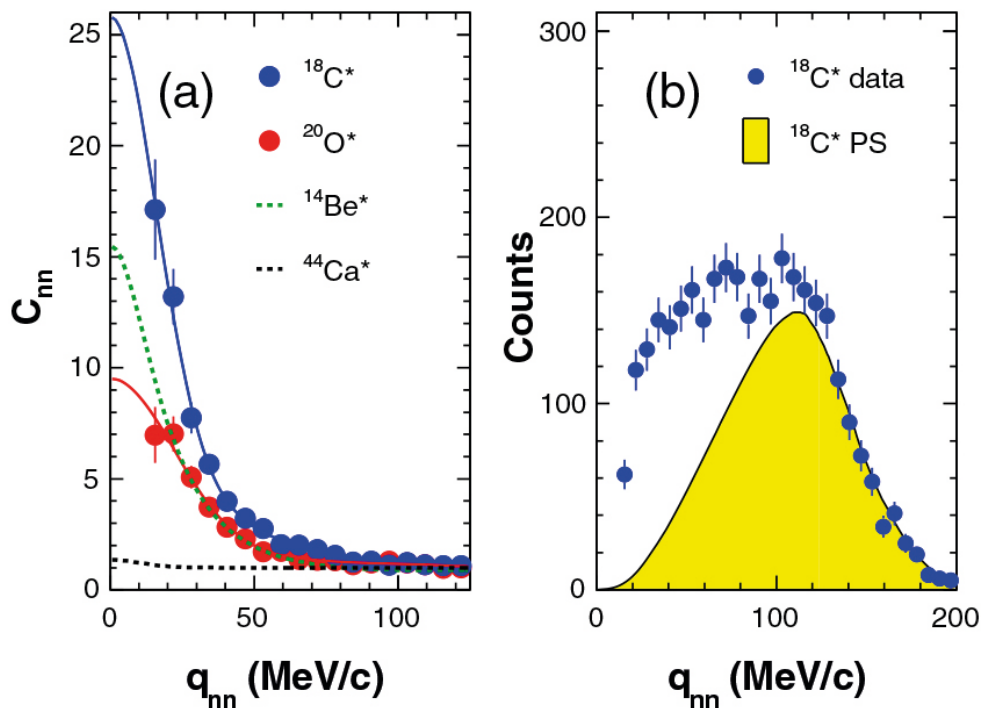


Figure 22. Neutron-Neutron correlation function (left) and decay spectrum compared to phase-space expectation (right). Figures from Ref. [2].

The second R<sup>3</sup>B result which we highlight here is the observation of strong neutron-neutron ( $nn$ ) pairing correlations in the decay of unbound states at the dripline. The results have been obtained from the same experimental run as discussed above. Here, the quasi-free scattering reaction was used to populate continuum states to investigate the role of  $nn$  pairing in neutron-rich nuclei. Results for the decay of  $^{18}\text{C}$  and  $^{20}\text{O}$ , produced respectively in  $(p,2p)$  and  $(p,pn)$  reactions, are shown in Figure 22. For  $^{18}\text{C}$ , surprisingly strong  $nn$  correlations are observed for decay energies above the  $4n$  threshold, which proceeds dominantly by direct  $2n$  emission. The correlation strength (blue symbols in Figure 22), the largest ever observed, suggests the predominance of a  $^{14}\text{C}$  core surrounded by four valence neutrons arranged in strongly correlated pairs. In contrary, a significant competition of a sequential branch and less pronounced  $nn$  correlations are found for the  $2n$  decay of  $^{20}\text{O}$  (red symbols). This is explained by the fact that  $^{20}\text{O}$  has been produced in a knockout reaction of a deeply bound neutron from  $^{21}\text{O}$  (populating highly excited continuum states) that breaks the  $^{16}\text{O}$  core and reduces the number of pairs.

## Outlook for 2019

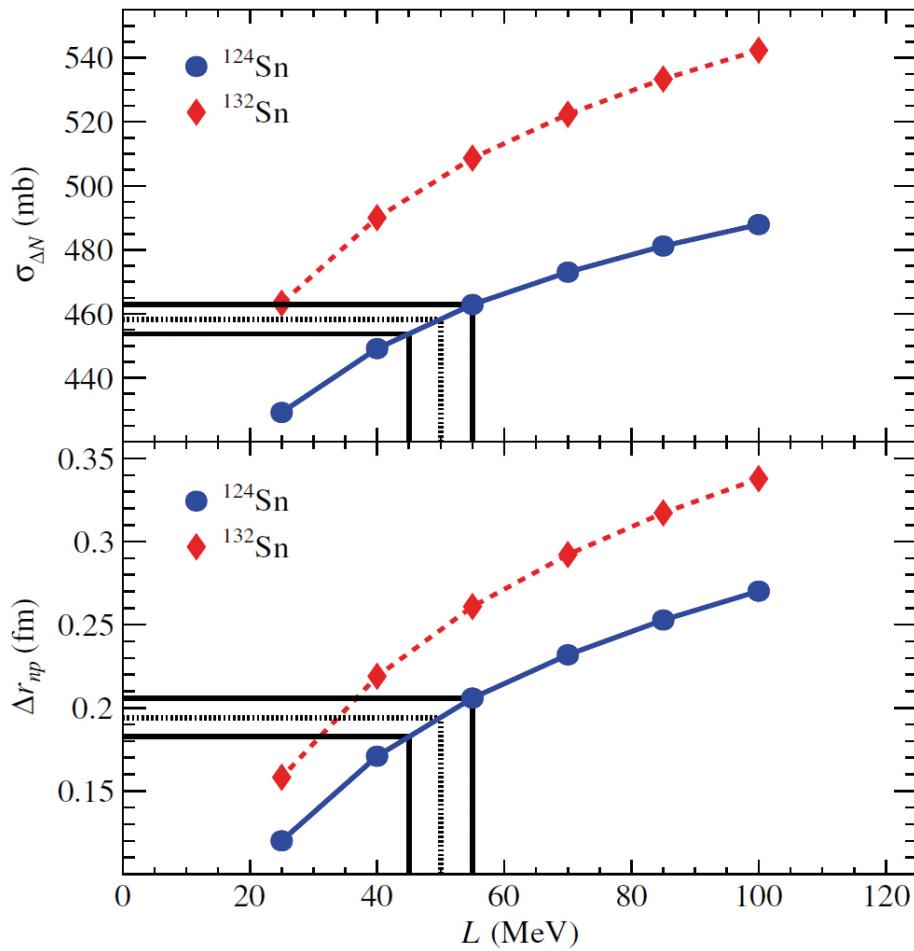


Figure 23. Relation between neutron-removal cross section (top) and neutron-skin thickness (bottom) with the symmetry-energy slope parameter  $L$  calculated based on relativistic mean field theory. The lines indicate the sensitivity of the observables. Figure from [T. Aumann et al., PRL 119 (2017) 262501].

R<sup>3</sup>B will see its first beams for physics production runs scheduled in the first half of 2019. The first experiment which will be performed will also mark the start of a new physics program at R<sup>3</sup>B aiming at tight experimental constraints on the symmetry-energy parameters, i.e., the equation of state for asymmetric nuclear matter. In theoretical studies it has been shown, that an accurate measurement of total neutron-removal cross sections from neutron-rich nuclei can provide such constraints. 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  $L$ , i.e., the neutron pressure, close to saturation density (see Figure 23). Since a large fraction of the volume of a neutron star has densities around nuclear saturation density, it is the very same neutron pressure that determines the neutron skins in heavy neutron-rich nuclei and the mass-to-radius relation of a neutron star. The experiment will provide first data for the stable  $^{120}\text{Sn}$  nucleus. Measurements will continue with neutron-rich isotopes including the doubly magic  $^{132}\text{Sn}$  and a first measurement beyond the N=82 neutron shell closure, as soon as beamtime with the FRS will be available.

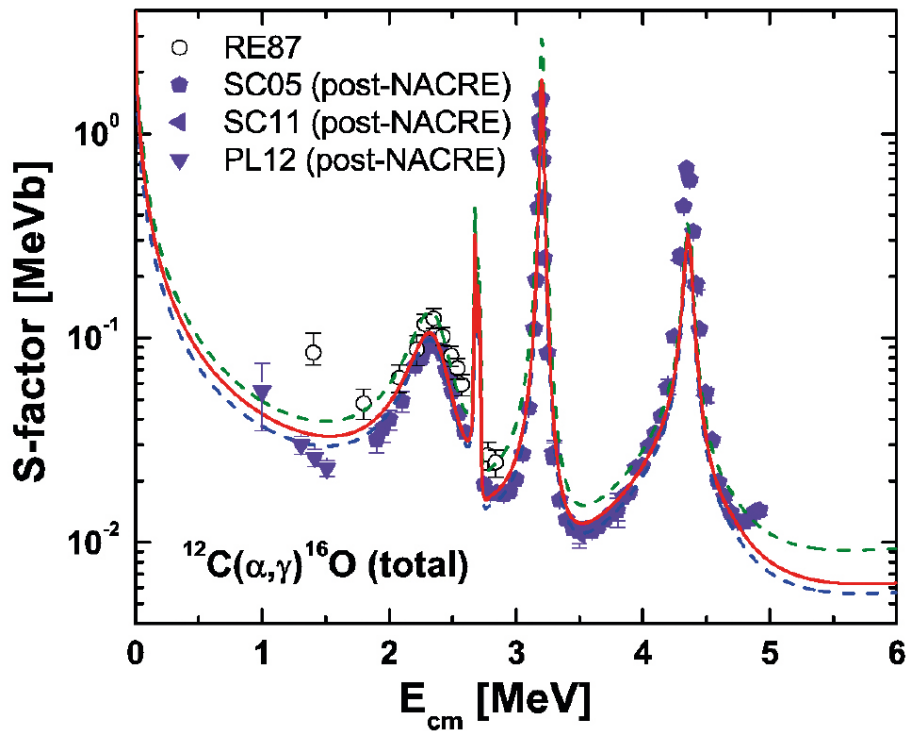


Figure 24. Astrophysical S-factor for the  $^{12}\text{C}(\alpha, \gamma)_{16}\text{O}$  reaction.

In the second experiment, the inverse reaction of one of the most important reactions in nuclear astrophysics will be measured, the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction, which determines the  $^{12}\text{C}/^{16}\text{O}$  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 energies  $E_{\text{cm}}$  where this reaction occurs in stars. R<sup>3</sup>B will measure the inverse  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  reaction by electromagnetic excitation at relativistic beam energies. The new R<sup>3</sup>B setup allows to reconstruct the relative energy of the fragments in the final state with high resolution and efficiency, and to cover a wide energy window in one setting including the resonance region, which reduces systematic normalization uncertainties. The goal is to determine the cross section and thus the astrophysical S-factor (see Figure 24) down to  $E_{\text{cm}}=800$  keV, which none of the many previous experimental attempts has accomplished.

### Selected publications of 2018

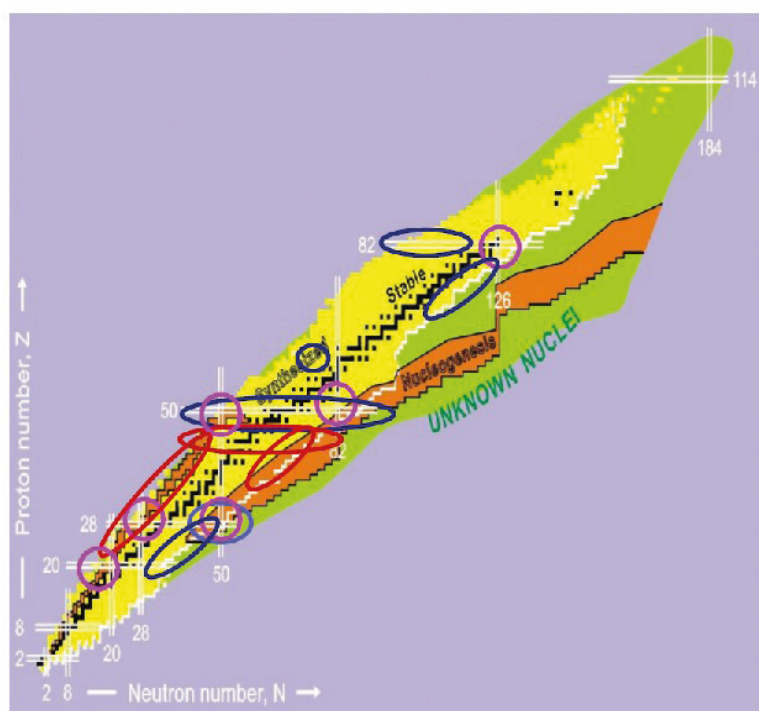
- [1] Atar, L. ; Paschalis, S. ; Barbieri, C. ; et al.: **Quasifree (p, 2p) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength.** *Physical review letters* 120(5), 052501 (2018) DOI:10.1103/PhysRevLett.120.052501
- [2] Revel, A. ; Marqués, F. M. ; Sorlin, O. ; et al.: **Strong Neutron Pairing in core + 4 n Nuclei.** *Physical review letters* 120(15), 152504 (2018) DOI:10.1103/PhysRevLett.120.152504
- [3] Wamers, F. ; Marganec, J. ; Aksouh, F. ; et al.: **Comparison of electromagnetic and nuclear dissociation of  $^{17}\text{Ne}$ .** *Physical review / C* 97(3), 034612 (2018) DOI:10.1103/PhysRevC.97.034612



## 4.3 Department Nuclear Spectroscopy

Head: Dr. Jürgen Gerl, GSI

Author: Dr. Jürgen Gerl, GSI



### Nuclear Shell structure

- $N \approx Z$
- $N \gg Z$

### Nuclear shapes

- Quadrupole, Octupole, Triaxiality
- Shape transitions
- High K-isomers

### Collective modes

- $N \gg Z$  : GDR soft mode

### Nuclear Symmetries

- mirror-isospin, pn-pair correlation

### Nuclear astrophysics

- r, rp process

Figure 25. Prominent nuclear spectroscopy topics. Image: J. Gerl/GSI Licence: ccby4

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 here: Gerl, J. ; Gorska, M. ; Wollersheim, H. J.: Towards detailed knowledge of atomic nuclei—the past, present and future of nuclear structure investigations at GSI. Physica scripta g1(10), 103001 (2016) DOI:10.1088/0031-8949/g1/10/103001. A kaleidoscope of main scientific topics is shown in Figure 25. 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 group coordinating the activities of the collaboration and developing and building the related infrastructure for the experimental campaigns at GSI and FAIR.

High-resolution In-flight SPECTroscopy (HISPEC) experiments are possible thanks to the unprecedented characteristics of AGATA, the Advanced GAMMA Tracking Array. The nuclei of interest are secondary reaction products following Coulomb excitation, direct reactions, or fragmentation reactions of relativistic radioactive ion beams provided by the FSR and in future by the Super-FRS at energies of 100-200 MeV/u. AGATA allows to disentangle the complex structure of excited states for the most exotic nuclei ever studied. The department is one of the key partners in the development of AGATA and hosted the early implementation of the spectrometer already from 2012 to 2014 [1].

Slowing down the rare isotope beams from FRS/Super-FRS to energies around the Coulomb barrier enables exploitation of classical reaction types like multiple Coulomb excitation, transfer reactions and compound nuclear reactions. This method is particularly useful for beam species not easily available at ISOL facilities. The slowing-down method and a suite of dedicated beam detectors is being developed by the department. Tying in with previous work, complementary close to the Coulomb barrier experiments at the UNILAC stable beam facility are planned for the near future as well.

Several DEcay SPECTroscopy (DESPEC) setups are being commissioned at different international accelerator laboratories. They are now available at GSI/FAIR for NUSTAR FAIR Phase-0 Experiments. These setups will deliver comprehensive decay information from identified key nuclei at secondary beam yields as low as one ion per hour. The department leads the development work for the DEGAS spectrometer, the most efficient dedicated high-resolution  $\gamma$  spectrometer for decay experiments worldwide. Furthermore, a fast, position-sensitive plastic detector for  $\beta$ -particle measurements in conjunction with the active AIDA implanter has been developed.

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

## Highlights in 2018

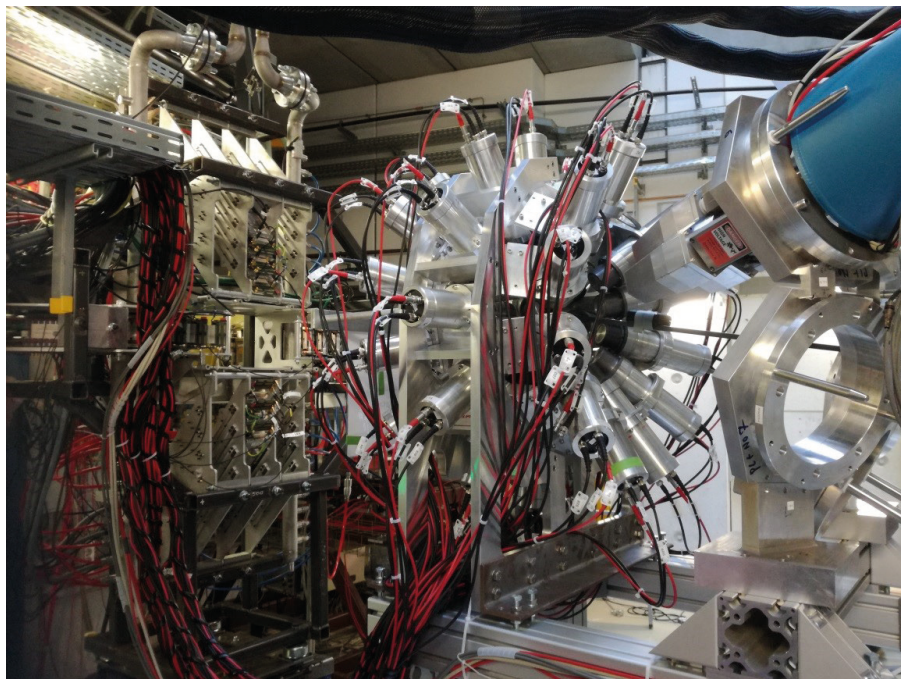


Figure 26. The DESPEC Fast-Timing Setup prepared for taking beam from the FRS. Photographer: J. Gerl/GSI  
Licence: ccby4

In 2018 activities concentrated on the preparation of the first DESPEC experiments within the FAIR/NUSTAR Phase-0 campaign. The early implementation of the so-called Fast Timing Setup was successfully installed on a movable platform at the s4 focal plane of the FRS. Figure 26 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 sub-systems are coupled together for the first time by the White Rabbit time stamping system.

The DEGAS detector system including its active shielding was modelled and simulated in detail [2] and the first Ge triple prototype has been produced and its characterization started. To overcome the limited

time resolution of the AIDA implanter a novel plastic detector b-Plast has been designed, built and successfully tested. It relies on a novel light readout scheme with Silicon Photomultipliers SiPMs [3] instead of conventional photomultipliers.

The HISPEC/DESPEC infrastructure TDR was finally submitted to the ECE of FAIR for evaluation. This TDR is a comprehensive description of the principle experiment setups, which will be realized at FAIR. New collaborators attracted by the unique GSI/FAIR facility have expressed their interest and will add to the versatility of HISPEC/DESPEC. For instance, recently the gSPEC project has been launched together with Australian and French groups aiming at the measurement of nuclear moments.

The analysis of previous PRESPEC AGATA experiments was on going and important results, e.g. ref. [Lalović, N. ; Rudolph, D. ; Podolyák, Z. ; et al.: Study of isomeric states in  $^{198,200,202,206}\text{Pb}$  and  $^{206}\text{Hg}$  populated in fragmentation reactions. Journal of physics / G G, Nuclear and particle physics 45(3), 035105 (2018) DOI:10.1088/1361-6471/aaagdf], are continuously emerging.

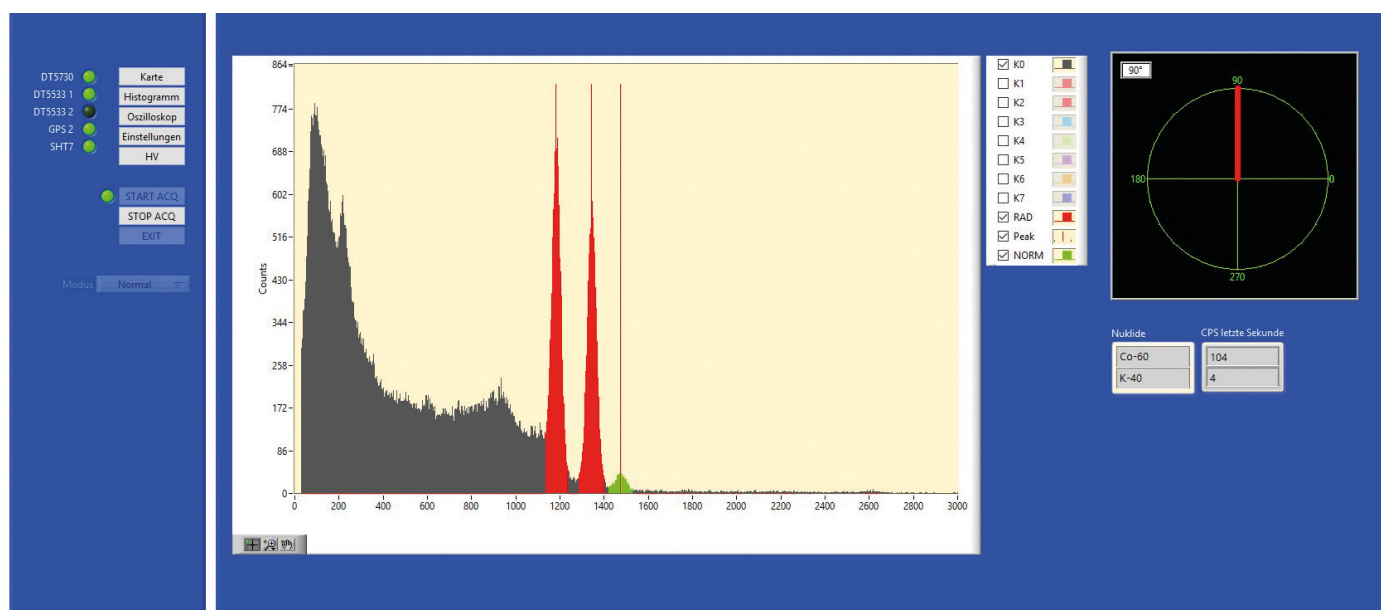


Figure 27. VIDEO-2 user interface depicting an environmental  $\gamma$  spectrum with identified "artificial"  $^{60}\text{Co}$  source (red lines) and its localized direction. Photographer: B. Löher/GSI Licence: ccby4

The radiation localizing system of the BMWi validation project VIDEO-2 $\gamma$  employing six  $\text{CeBr}_3(\text{TI})$  scintillator crystals has been assembled and the testing has started. Figure 3 shows a representation of the graphical user interface with an environmental background spectrum including the typical  $^{40}\text{K}$  line (green line). The software (red lines) identified an "artificial"  $^{60}\text{Co}$  source deployed in the test environment and determined its direction.

## Outlook for 2019

In 2019 it is planned to commission the DESPEC Fast Timing Setup at the FRS and optimize it for experiments starting in 2020. The production of the DEGAS Ge detector array will start after thoroughly testing the prototype. These tests include characterization on the 3D  $\gamma$ -scanner, a sophisticated instrument developed and operated by the department. Upgrade measures for the scanner to speed up the calibration process by employing a novel active grid are planned in this context.

To enlarge the experimental basis it is planned to refurbish the old X7 cave in order to become operational for UNILAC experiments from 2020 onwards. Meanwhile nuclear spectroscopy experiments are planned to continue at other international facilities.

The direction sensitive  $\gamma$ -detector developed for security applications will be developed within the VIDEO-2 $\gamma$  project. This novelty will have unprecedented sensitivity and a direction accuracy of  $<3$  degrees, enabling the localization of enhanced  $\gamma$  radiation by triangulation.

## Selected publications of 2018

- [1] Clément, E. ; Gadea, A. ; Gerl, J.: **The AGATA Campaigns at GSI and GANIL.** *Nuclear physics news* 28(3), 16 - 19 (2018) DOI:10.1080/10619127.2018.1495478
- [2] Li, G. S. ; Lizarazo, C. ; Gerl, J. ; et al.: **Simulated characteristics of the DEGAS -detector array.** *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A* 890, 148 - 154 (2018) DOI:10.1016/j.nima.2018.02.062
- [3] Cortés, M. L. ; Reese, M. ; Doublet, S. ; et al.: **Silicon photomultipliers as readout for a segmented Time-of-Flight plastic detector.** *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A* 899, 101 - 105 (2018) DOI:10.1016/j.nima.2018.05.031
- [4] Lalović, N. ; Rudolph, D. ; Podolyák, Z. ; et al.: **Study of isomeric states in  $^{198,200,202,206}\text{Pb}$  and  $^{20}\text{Hg}$  populated in fragmentation reactions.** *Journal of physics / G G, Nuclear and particle physics* 45(3), 035105 (2018) DOI:10.1088/1361-6471/aaagdf



## 4.4 Department SHE Chemistry and SHE Physics

Heads: Prof. Dr. Christoph Emanuel Düllmann, Johannes Gutenberg-Universität Mainz & GSI, Prof. Dr. Michael Block, Johannes Gutenberg-Universität Mainz & GSI

Authors: Prof. Dr. Michael Block, Prof. Dr. Christoph E. Düllmann, Dr. Francesca Giacoppo, Dr. Jadamba Khuyagbaatar, Dr. Valeria Pershina, Dr. Sebastian Raeder, Dr. Alexander Yakushev

The activities of the SHE Physics and SHE Chemistry departments in 2018 were first focused on the implementation of facility upgrades during the extended period without UNILAC operation, and then on the 2018 UNILAC beamtime block. Selected experiments of the Superheavy Element Chemistry department were performed abroad at JAEA Tokai, Japan. In the following, the most important research topics are briefly summarized.

### Highlights in 2018

#### High-precision mass measurements

The 2018 beamtime campaign at SHIPTRAP allowed extending direct high-precision mass measurements to more exotic nuclides. Thanks to a cryogenic gas stopping cell that was installed in the extended shutdown in 2017/18, measurements were performed more efficiently giving access to the superheavy nuclide  $^{257}\text{Rf}$  ( $Z=104$ ), representing the first such measurement beyond the end of the actinide series. In addition, using the novel PI-ICR technique, originally developed at SHIPTRAP, the masses of the isotopes  $^{251,254\text{m}}\text{No}$  and  $^{254-256}\text{Lr}$  were measured with statistical uncertainties on a  $10^{-9}$  level. This was the first time that this technique has been applied under extreme conditions of lowest production rates. Exploiting the high mass resolving power up to 10,000,000, low-lying isomers with tens of keV excitation energies  $^{251\text{m}}\text{No}$  and  $^{254\text{m},255\text{m}}\text{Lr}$  were identified unambiguously. Such measurements are presently only possible at SHIPTRAP. The data analysis is close to completion. A particular focus was on the investigation of systematic uncertainties in the PI-ICR method and a first publication is in preparation.

#### Laser spectroscopy

The analysis of the 2016 laser spectroscopy campaign of nobelium at GSI was completed and the results were published in two papers in Phys. Rev. Lett. [1,2]. From more than 30 identified atomic states in nobelium, its first ionization potential was determined with high accuracy. Hyperfine spectroscopy of  $^{253}\text{No}$  confirmed a ground state spin parity of  $9/2^+$  and provided nuclear model-independent values for the quadrupole moment and the magnetic moment. In addition, differential charge radii for  $^{252-254}\text{No}$  were obtained. The results were in excellent agreement with theoretical work, which accompanied the experimental efforts. The laser spectroscopy on nobelium isotopes and the search for atomic levels in the heavier element lawrencium is scheduled for the 2019/2020 beamtime campaign.

A new setup for high-resolution laser spectroscopy using an in-gas jet approach originally developed by KU Leuven has recently been built in Mainz. The online commissioning at GSI is foreseen to start in 2019 with experiments on the radioisotope  $^{155}\text{Yb}$ . An experiment to determine the structure of the  $8^-$  K-isomer in  $^{254\text{m}}\text{No}$  has been approved by the GSI PAC and is planned to be performed in 2020.

#### Nuclear reactions

A focus was on the study of nuclear reactions which do not lead to fusion. In a first paper, results from a detailed analysis of reaction products detected during the  $^{50}\text{Ti}+^{249}\text{Cf}$  irradiation performed in 2012 were published, which yielded information on properties of non-fusion reactions in this system [3]. A second paper reported results obtained in collaboration with the Australian National University, Canberra, addressing differing fusion probabilities in the  $^{48}\text{Ti} + ^{204,208}\text{Pb}$  and the  $^{50}\text{Ti} + ^{206,208}\text{Pb}$  reactions [4].

## Nuclear structure

TASCA underwent several upgrade measures in 2018 and was thereafter commissioned with parasitic beam; this was used to simultaneously perform some physics measurements, e.g., on  $^{250}\text{No}$  or the hitherto unknown  $^{244}\text{Md}$ . For this, the updated TASCA focal plane detection systems with full digital electronics on Febex4-basis, which is a development of the Experiment Electronics Laboratory at GSI, was used. The data analysis is close to completion and a first publication is in preparation.

Besides preparations for the approved nuclear spectroscopy experiment on Fl and its daughters, analysis of the data set acquired in 2012 with an emphasis on “unwanted” background products was continued, and refined data on  $^{219}\text{Ra}$  and  $^{215}\text{Rn}$  was obtained by the collaborators from Lund University, Sweden [5]. At SHIP the commissioning of the new focal plane detector setup COMPASS was completed [6]. This system comprises a compact box geometry with pixelized silicon strip detectors that can be surrounded by Ge detectors for efficient alpha-gamma spectroscopy. Further improvements of the SHIP decay spectroscopy setup have been tested in the 2018 UNILAC engineering run. First experiments with COMPASS on neutron-deficient Np and Pa isotopes have been performed by Lund University, and the results will soon be published.

## SHE Chemical Properties

In past beamtimes, experiments on the chemical behaviour of Fl and Nh in comparison with Hg, Tl, Pb, and Rn were performed at TASCA, and a paper focusing on the lighter homologs was published in 2018 [7]. The focus of the next experiments is on Nh, member of group 13 and a homolog of Tl. To lend assistance to the current suite of gas-phase chromatography experiments at TASCA on the volatility and reactivity of Nh. With the Amsterdam Density Functionale ADF calculations of adsorption energies of group-13 hydroxyls (of Tl and Nh) on gold were performed and published [8,9]. The results have shown that the trend in adsorption of MOH,  $\text{TlOH} < \text{NhOH}$ , is opposite to the one of the atoms, where  $\text{Tl} > \text{Nh}$ . The adsorption enthalpies of Nh and NhOH were found to be very similar, so that the identification of the chemical composition by measuring adsorption temperature will be difficult. Experimental work focused on establishing the optimum experimental setup and operation parameters for the main experiment on Nh chemistry, which is scheduled to take place at the UNILAC at GSI in 2020. For this, the combination of an improved version of the gas phase chromatography setup COMPACT, termed miniCOMPACT and adapted to short-lived more reactive species, with the TASCA separator has been optimized, studying different coupling options including a traditional gas-filled Recoil Transfer Chamber (RTC) as well as the previous SHIPTRAP buffer-gas stopping cell equipped with DC gradient and RF repeller funnel. In online experiments the short-lived isotopes  $^{204,205}\text{Fr}$ , produced via the reaction  $^{40}\text{Ar} + ^{169}\text{Tm}$ , were successfully extracted from the RTC into miniCOMPACT. The experiments with the RTC-miniCOMPACT combination were carried out in the 2018 beamtime period, while those with the buffer-gas-cell/miniCOMPACT combination are foreseen for the 2019 beamtime period. In preparation of the latter, off-line measurements were performed with  $^{223}\text{Ra}$  and  $^{225}\text{Ac}$  recoil ion sources installed in the buffer gas stopping cell. In separate experiments, the gas-catcher-COMPACT-setup as well as the new RTC-miniCOMPACT setup were flushed with helium gas and allowed performing gas phase chromatography studies the recoil ions  $^{219}\text{Rn}$  ( $T_{1/2} = 3.96\text{ s}$ ) or  $^{217}\text{At}$  ( $T_{1/2} = 32.3\text{ ms}$ ). The efficiency for transporting these isotopes from the source to the COMPACT detector as well as the transport time were studied.

The studies of volatile transition metal carbonyl complexes with short-lived isotopes has been continued, using the two-chamber technique which was developed last year. Building up on the successful experiments with fission products at TRIGA Mainz, which focused on studying and optimizing the partial efficiency of the flushing-out the first into the second chamber, an on-line experiment with the heavier homologs was carried out at JAEA Tokai. This confirmed that such an approach allows obtaining higher efficiencies than with preseparation, however, rather long-lived isotopes were used to minimize the influence of kinetic effects. The latter will be studied in coming experiments with short-lived alpha-decaying isotopes, for which beamtime is approved at JAEA Tokai as well as at RIKEN, Wako. With the aim to support gas-phase experiments on study of stability and volatility of carbonyls of the heaviest elements, calculations of the electronic structures and properties of group-7 carbonyls, including those of Bh, were published [10]. The most advanced relativistic quantum-chemical methods (ADF BAND, X2c-DFT, DIRAC) were utilized, and properties of the  $\text{M}(\text{CO})_5\text{H}$  species ( $\text{M} = \text{Tc}, \text{Re}$  and  $\text{Bh}$ ) have been determined, including radicals  $\text{M}(\text{CO})_5$ . Volatility of these species and first bond dissociation energies were predicted.

## Outlook for 2019

The UNILAC beamtime in spring 2019 will be the main activity with a focus on laser spectroscopy of nobelium and lawrencium at SHIP, on the spectroscopy of flerovium decay chains at TASCA, and parasitic beamtimes at both devices to perform parameter studies, e.g., in preparation of the approved beamtime on nihonium chemical properties planned for 2020.

## Selected publications of 2018

- [1] Raeder, S. ; Ackermann, D. ; Backe, H. ; et al.: **Probing Sizes and Shapes of Nobelium Isotopes by Laser Spectroscopy.** *Physical review letters* 120(23), 232503 (2018) DOI:10.1103/PhysRevLett.120.232503
- [2] Chhetri, P. ; Ackermann, D. ; Backe, H. ; et al.: **Precision Measurement of the First Ionization Potential of Nobelium.** *Physical review letters* 120(26), 263003 (2018) DOI:10.1103/PhysRevLett.120.263003
- [3] Di Nitto, A. ; Khuyagbaatar, J. ; Ackermann, D. ; et al.: **Study of non-fusion products in the  $^{50}\text{Ti} + ^{249}\text{Cf}$  reaction.** *Physics letters / B B* 784, 199 - 205 (2018) DOI:10.1016/j.physletb.2018.07.058
- [4] Khuyagbaatar, J. ; David, H. M. ; Hinde, D. J. ; et al.: **Nuclear structure dependence of fusion hindrance in heavy element synthesis.** *Physical review / C* 97(6), 064618 (2018) DOI:10.1103/PhysRevC.97.064618
- [5] Sămark-Roth, A. ; Sarmiento, L. G. ; Rudolph, D. ; et al.: **Low-lying states in  $^{219}\text{Ra}$  and  $^{215}\text{Rn}$  : Sampling microsecond -decaying nuclei.** *Physical review / C covering nuclear physics* 98(4), 044307 (2018) DOI:10.1103/PhysRevC.98.044307
- [6] Ackermann, D. ; Mistry, A. K. ; Heßberger, F. ; et al.: **COMPASS—A COMPACT decay spectroscopy set-up.** *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A* 907, 81 - 89 (2018) DOI:10.1016/j.nima.2018.01.096
- [7] Lens, L. ; Yakushev, A. ; Düllmann, C. E. ; et al.: **Online chemical adsorption studies of Hg, Tl, and Pb on  $\text{SiO}_2$  and Au surfaces in preparation for chemical investigations on Cn, Nh, and Fl at TASCAK.** *Radiochimica acta* 2017-2914(0), 1-14 (2018) DOI:10.1515/ract-2017-2914
- [8] Pershina, V. ; Iliaš, M.: **Electronic structure and properties of MAu and MOH, where M = Tl and Nh: New data.** *Chemical physics letters* 694, 107 - 111 (2018) DOI: 10.1016/j.cplett.2018.01.045
- [9] Pershina, V.: **Reactivity of Superheavy Elements Cn, Nh, and Fl and Their Lighter Homologues Hg, Tl, and Pb, Respectively, with a Gold Surface from Periodic DFT Calculations.** *Inorganic chemistry* 57(7), 3948 - 3955 (2018) DOI:10.1021/acs.inorgchem.8b00101
- [10] Pershina, V. ; Iliaš, M.: **Carbonyl compounds of Tc, Re, and Bh: Electronic structure, bonding, and volatility.** *The journal of chemical physics* 149(20), 204306 (2018) DOI:10.1063/1.5055066





## 5. Research of the PANDA Departments

Coordinator: 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 multipurpose detector. The combination of a high-quality antiproton beam at the HESR, an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. GSI together with the Helmholtz-Institut Mainz is the PANDA lead-lab which coordinates the international efforts of the whole PANDA collaboration (73 institutes in 20 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 and the Gas Electron Multiplier (GEM) detector. This is accompanied by FAIR 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 Institute Mainz and with the PANDA Coordinators at FAIR.

### Highlights in 2018

The first highlight in 2018 is the definition of the FAIR Day-1 setup of PANDA which accounts for the available funding, production schedules and the needs of the early physics program, which implied a lot of simulation and engineering work. Core systems of the Day-1 setup are the cluster-jet target, the solenoid magnet with the muon system, the micro vertex detector, the straw tube tracker, the Barrel DIRC and Barrel ToF, the forward and backward endcaps of the EMC, 12 slices (out of 16) of the Barrel EMC, 2 stations (out of 3) of the GEM detector and 4 (out of 6) stations of the forward tracker, the Forward ToF, the Forward calorimeter and the Luminosity Detector. There are advanced investigations to cover the 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 committees.

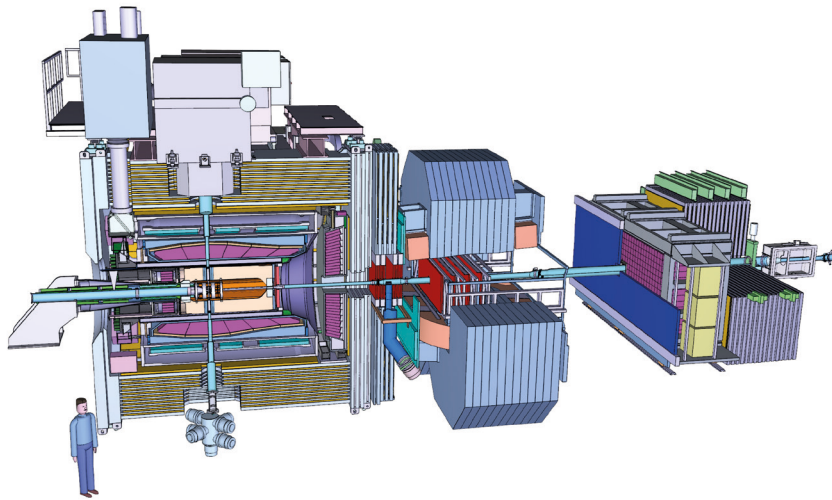


Figure 28. Drawing of the PANDA FAIR Phase-1 Detector.

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 FAIR 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.

An important milestone and thus another highlight is the start of the solenoid construction and the completion of the first octant of the magnet. All octants will be completed in 2019 and a control assembly will be performed. In addition, cooperation for the R&D of the manufacturing of the PANDA super-conductor with two Russian institutes, VNIIEP (Podolsk) and VNIINM (Bochvar), has been established. This was necessary since the originally foreseen provider Furukawa presently cannot do Aluminium co-extrusion anymore. First tests of the extrusion method were successful.

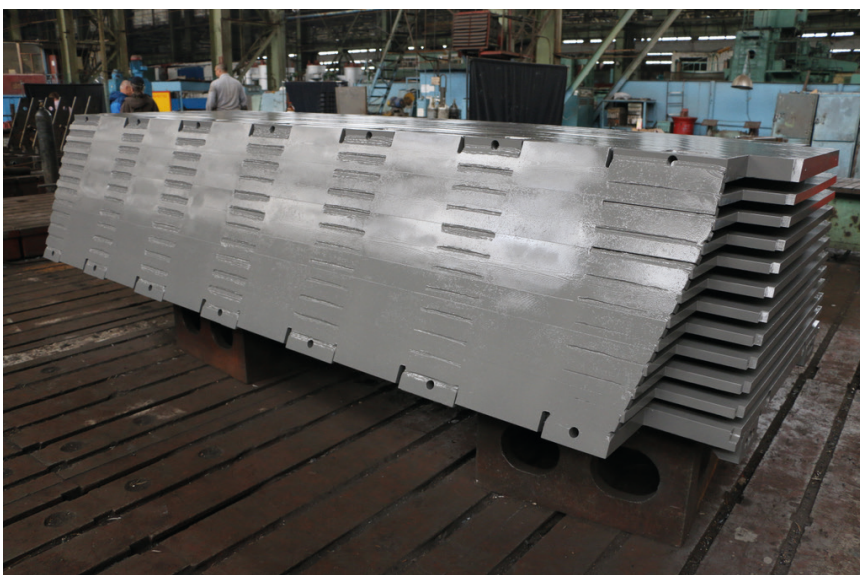


Figure 29. Left: First octant of the iron yoke for the PANDA Solenoid Magnet. Right: Rear part of the iron yoke for the PANDA Solenoid Magnet.

Finally, a design contract for the development of the dipole magnet, which is an integral part of the ion optic layout of HESR, was signed by BINP and FAIR and will cover all work necessary prior to actual construction of the magnet.

Analysis wise, an important feasibility study has been finalized and published. Although being the first of the new charmonium-like states discovered since 2003, the  $X(3872)$  is still one of the most puzzling ones concerning its nature. 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  $J/\psi p^0$  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  $\Gamma_X \geq 100 \text{ keV}/c^2$  will be accessible with  $3\sigma$  significance 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

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 for PANDA is an important aspect and a concept was defined in 2018. In particular the sequence of events was detailed starting with the magnets and support structures in the first installation window and the following steps of the assembly of the target spectrometer. In future the concept of sharply defined installation windows needs to 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 beam-pipe and vacuum system in PANDA has started in 2018. Specifications of the pipe along the beam axis, positioning of vacuum pumps and interfaces with detectors and target systems are under investigation and first design studies and hardware prototypes are under way. Additional aspects involving the PANDA target are part of the R&D contract with the University Muenster as well as the connection to the luminosity measurement together with the University Bochum.

A lot of progress has been made in the analysis of BESIII data. The focus is on decay channels of the enigmatic vector resonance  $Y(4260)$  in electron positron annihilations. The technique of inclusive recoil spectral analysis is used to identify missing channels and to map out the line shape of the object from an energy scan of the colliding beams. Recoil studies are performed with pions, kaons, (anti-)protons and hyperons and preliminary results have been presented.

The data analysis of GlueX has recently started with the focus on strangeonium hybrids, long-awaited exotic mesons with an excited gluon field with a strange-anti-strange meson composition. This is expected in hard photon nucleus scattering with a trigger on the  $\phi$  resonance in the decay to  $K^+K^-$ .



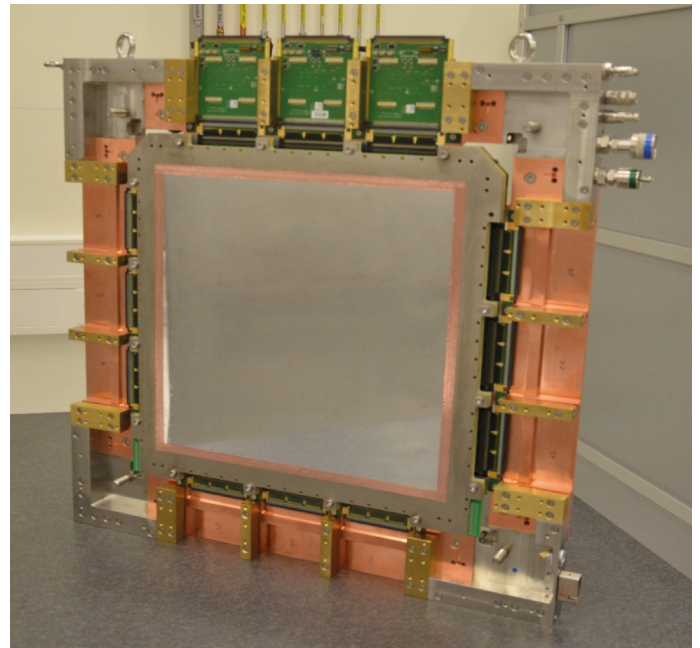
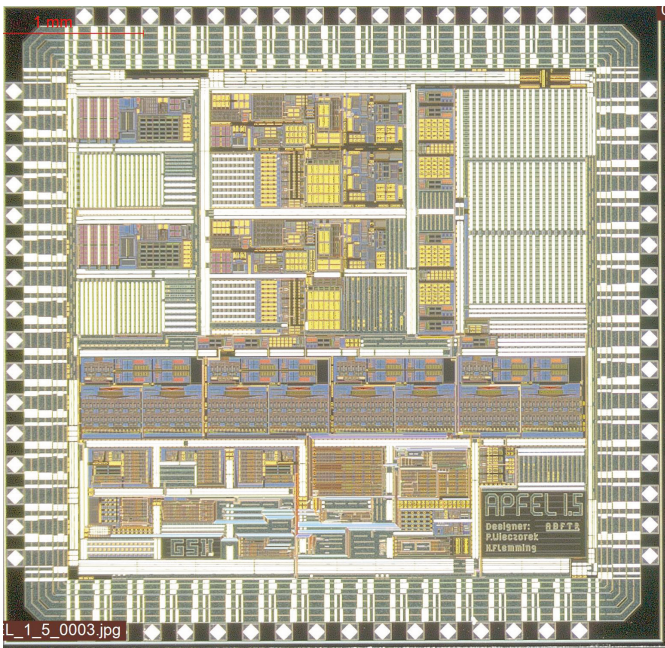


Figure 30. Left: : Die of the Apfel chip, a multi-channel low-noise preamplifier for the PANDA EMC. Right: 2D demonstrator for the PANDA GEM detector.

In cooperation with the Electronics Lab the preamplifier and hitdetection asics for the EMC have been developed and the preamplifier is now available for mass assembly (see Figure 30). Together with the Detector Lab the screening of the Large Area Avalanche Photo Diodes (LAAPDs) for the EMC is on-going and both activities are complemented by additional R&D work by the Universities Bonn and Bochum. Another development together with the Detector Lab is the GEM Detector. A 2D demonstrator for the PANDA GEM was finished in 2018 (see Figure 30) and a TDR is near to finalization.

## 5.2 PANDA detector developments

Head: Dr. Joachim Schwiening, GSI  
 Author: Prof. Dr. Klaus Peters

The main objective of the department is the development and construction of solid-state Cherenkov Detectors commonly known as Detectors of Internally Reflected Cherenkov Light (DIRC) based on synthetically fused silica with appropriate fast optical read-out for single photons to measure the velocity of particles.

After the approval of the TDR for the Barrel DIRC the final design issues and the preparation for the production and assembly procedures have been the main focus of the work detailed below. The group cooperates with the Universities of Erlangen and Gießen, the Helmholtz-Institut Mainz as well as the PID groups from GlueX@JLAB and the Electron-Ion Collider EIC consortium. The in-kind contract for the Barrel DIRC was signed in August 2018.

Simulation effort have been undertaken to help decide if some of the fabrication tolerances on the fused silica bars and MCP-PMTs can be relaxed to further save costs. In addition, the Barrel DIRC prototype was successfully evaluated with a mixed hadron beam in the T9 beam line at the CERN PS in July/August 2018 during a joint beam test campaign with the Endcap Disc DIRC prototype and a SciTil prototype. During 18 days of beam time, the Barrel DIRC team from Erlangen, Frankfurt, and GSI recorded some 640 M events for a range of momenta and angles corresponding to the expected final state phase space of pions and kaons in PANDA. A key result was the measurement of the PID performance of a cost-saving sensor arrangement with 8 instead of 11 Microchannel-Plate PMTs per sector. The preliminary analysis shows that the number of sensors can be reduced by 25% without a significant deterioration in the performance or robustness of the design. Further analysis of data is ongoing. The lens system is currently being optimized.

The DIRICH Frontend electronics will replace the PADIWA/TRB readout chain. This avoids the use of analog signal transmission cables, since the sensor signals are transmitted via the backplane PCB traces to the FPGA boards. The DIRICH backplanes are now available and first tests have started at GSI.

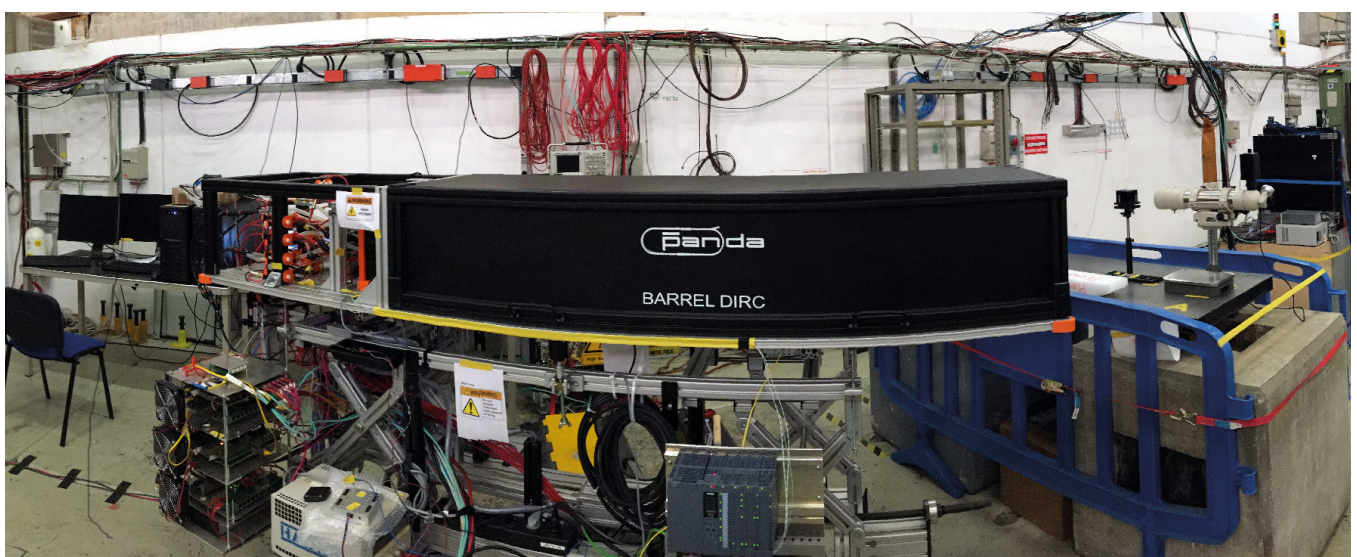


Figure 31. Test setup for the PANDA DIRC at CERN.

The upgrade of the GlueX experiment at Jefferson Lab with a DIRC counter is expected to significantly improve the particle identification (PID) capabilities and to extend the physics reach for the



GlueX-II run, scheduled to start in late 2019. The GlueX DIRC comprises four bar boxes from the decommissioned BaBar experiment, forming a forward PID wall, 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. This unique opportunity was used to validate and optimize simulation and reconstruction algorithms, developed originally for the PANDA Barrel DIRC, using GlueX data, as part of FAIR Phase-0. Although the alignment and calibration of the data is preliminary, the performance indicators are in a good agreement with the expected theoretical values. The obtained single photon resolution of 9-10 mrad is consistent with the expectation from simulation. The readout system for the upper bar boxes will be installed and commissioned in 2019, which will provide additional data to further tune simulation parameters, optimize the reconstruction, and test PID calibration methods for the PANDA Barrel DIRC.

## Outlook for 2019

A task force for the machine installation took up its work. The installation strategy, requirements on logistics and resources and work description are addressed by this group. To collect the required input PANDA holds a series of installation workshops in 2019. Major tasks towards the Day-1 configuration is the completion and submission of the last three TDRs for this initial setup. They comprise the Detector Controls Systems (DCS), 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.

With the tendering and contracting of major components for the Barrel DIRC being finalized in 2019, production will start and assembly planning will commence towards a production readiness assessment.

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 after 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 2018

- Liu, Z.-A. ; Dzhygadlo, R. ; Ali, A. ; et al.: **The Barrel DIRC Detector for the PANDA Experiment at FAIR**. In: *Proceedings of International Conference on Technology and Instrumentation in Particle Physics 2017* / Liu, Zhen-An (Editor) ; Singapore : Springer Singapore, 2018, Chapter 25 ; DOI:10.1007/978-981-13-1313-4\_25
- Schwiening, J. ; Ali, A. ; Belias, A. ; et al: **The PANDA Barrel DIRC**. In: *International Workshop on Fast Cherenkov Detectors - Photon detection, DIRC design and DAQ, DIRC2017, Schloss Rauischholzhausen, Germany, 7 Aug 2017 - 9 Aug 2017 Journal of Instrumentation* 13(03), C03004 - C03004 (2018) DOI:10.1088/1748-0221/13/03/C03004
- Divani Veis, N. ; Firoozabadi, M. M. ; Karabowicz, R. ; et al.: **Performance studies of the PANDA planar GEM-tracking detector in physics simulations**. *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment Section A* 884, 150 - 156 (2018) DOI:10.1016/j.nima.2017.11.096





## 6. Research of the department Theory

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

Author: 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 Simulations lead by Hannah Elfner. The following provides a summary of the research performed in 2018.

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. Strong synergies exist with the NUSTAR program at FAIR.

### Highlights in 2018

The first core-collapse supernova simulations that explicitly include the production of muons by both thermal and weak processes were performed [Bollig et al, Phys. Rev. Lett. 119, 242702 (2017)]. This required the development of a full set of neutrino interactions involving muons and the development of six-flavour radiation neutrino-transport-models. It is found that weak processes are very efficient in producing muons, thus softening the equation of state and triggering a faster contraction of the neutron star. This in turn, leads to higher luminosities and mean energies of the emitted neutrinos that facilitate explosions by the neutrino-driven mechanism. The temperatures reached in the neutron star core,  $T \sim 50$  MeV, are high enough that other low mass particles, like pions, could be produced. The impact of pions in the simulations remains to be explored, but nicely connects with the physics program of HADES and CBM, where similar conditions are probed in heavy ion collisions. DOI:10.1103/PhysRevLett.119.242702

Neutrinos in supernova are not only fundamental for the explosion but they also play an important role in the nucleosynthesis of elements by the neutrino-process in which neutrino neutral- and charged-current processes operating in the stellar mantle contribute to the production of several elements. We have performed studies of neutrino-nucleosynthesis based on modern predictions of neutrino spectra and a full set of neutrino-nucleus reactions for a broad range of progenitor stars [A. Sieverding et al, Astrophys. J. 865, 143 (2018)]. Despite the reduced average neutrino energies predicted by modern supernova simulations, we find that the neutrino process contributes noticeable to the solar yields of  $^{11}\text{B}$ ,  $^{15}\text{N}$ ,  $^{19}\text{F}$ ,  $^{138}\text{La}$ , and  $^{180}\text{Ta}$ .

Thermodynamic properties and the chemical composition of dense matter are important ingredients in the simulation of neutron star mergers and core-collapse supernovae. Such studies allow, in comparison to astronomical observations, to constrain theoretical models for the equation of state (EoS) of strongly interacting matter. New EoS tables were provided with a systematic variation of the density dependence of the nuclear symmetry energy [S. Typel, J. Phys. G 45, 114001 (2018)] employing a generalized relativistic density functional. The parameters of the model were obtained in fits to properties of nuclei applying the Lagrange-mesh method in the nuclear structure calculations [S. Typel, Frontiers in Physics 6, 73 (2018)]. The dependence of nuclear matter parameters on the functional form of the density dependent nucleon-meson couplings was studied systematically [S. Typel, Particles 1, 3 (2018)]. A phenomenological description of the hadron-quark phase transition at high densities and temperatures was introduced in the density functional [S. Typel and D. Blaschke, Universe 4, 32 (2018)]. It is based on an extension of the excluded-volume mechanism that allows to reinterpret the approach as a simple method to describe a change of the effective number of degrees of freedom.

The main goal of heavy-ion research is to probe and understand the properties of strongly-interacting matter, in particular the structures in the phase diagram of QCD matter. By colliding heavy ions at almost the speed of light, temperatures and densities are reached as they existed in the early universe or in collisions of astrophysical objects. Within the GSI-FAIR program, CBM and HADES explore the dense region

of the phase diagram. The underlying field theory of the strong interaction, namely quantum chromodynamics (QCD), cannot be used to directly solve this many-body problem. Therefore, effective approaches become necessary. Transport approaches are microscopic non-equilibrium descriptions of the relevant degrees of freedom (hadrons or partons) and provide information of the full space-time information of all interactions occurring in heavy-ion collisions. These approaches are providing the essential link between QCD properties and the experimental measurements. Pursuing this type of research, it is crucial to solve the same problem with different techniques and focusing on different aspects. Therefore, within the group at GSI there are several complementary approaches being developed.

Neural networks have attracted considerable attention both in science articles and in the general media. Recent interest has been sparked by advances in “deep learning” methods, which are now capable of producing preliminary versions of artificial intelligence. In this work [L.-G. Pang et al., *Nature Commun.* 9, 210 (2018)], a convolutional neural network has been employed to decode the sensitivities of final state momentum space distributions of particles produced in high-energy heavy-ion reactions to the equation of state of strongly interacting matter. One of the major goals of CBM at FAIR will be the determination of the nature of the transition between the quark-gluon plasma and the hadronic phase. As a proof of principle, it has been shown that it is feasible to encode features of the dynamic evolution with different transition types (crossover versus first-order phase transitions) in a neural network that is trained on hydrodynamic simulations. The results are encouraging, with a recognition probability on completely independent testing data sets above 95%. The resulting importance maps provide guidance for constructing sensitive observables. DOI:10.1038/s41467-017-02726-3

The microscopic transport approach for the dynamical description of strongly interacting matter as created in heavy-ion collisions —PHSD (Parton-Hadron-String Dynamics)— has been further developed with respect to an explicit dependence of the partonic interactions on the finite baryon chemical potential and temperature. This allows to explore the traces of the baryon chemical potential dependence on experimental observables which is relevant, in particular, for the future FAIR and NICA facilities as well as for the interpretation of the RHIC-BES data.

The newly developed hadronic transport approach Simulating Many Accelerated Strongly-interacting Hadrons (SMASH), which was the major goal of the Helmholtz Young Investigator Group VH-NG-822, has been established in the context of experimental measurements from GSI-SIS18 within the FOPI and HADES collaborations. In particular a thorough comparison to the available dilepton measurements has been performed, which are sensitive to the medium modifications of hadrons in dense matter (DOI: 10.1103/PhysRevC.98.054908 ). The source code has been published in November 2018 and is available under [smash-transport.github.io](https://github.com/smash-transport).

A reliable theoretical description of coupled systems subject to strong interactions is still one of the remaining fundamental challenge of modern physics. So far, effective field theory approaches with hadronic degrees of freedom that reflect QCD properties are established only for particular corners in the femto cosmos of strong interactions. At energies where QCD forms bound states or resonances there is a significant lack of profound theory that connects to experimental data directly. Despite the tremendous efforts and successes of experimental accelerator facilities and emerging lattice gauge theory simulations there is a significant gap in what theory can accomplish and experimental groups at FAIR would need to be properly guided in new searches for exotic matter.

Two major advances have been achieved recently. First, it was demonstrated that from current QCD lattice data at non-physical quark masses it is possible to derive effective hadronic interactions that can be used to derive the coupled-channel dynamics as measured in the laboratory. Specific predictions relevant for the open-charm physics program of BELLE, LHCb and PANDA are worked out already. In particular, the existence of scalar and axial vector resonances in an exotic flavor sextet are foreseen. Such states should have impact in Dalitz plot analysis of B meson decays but also leave their trace in  $\eta D$  and  $\eta D^*$  invariant mass distributions. DOI:10.1103/PhysRevD.98.014510

More results relevant for the baryon resonance program at HADES and PANDA are in preparation. Here the most important effective interactions are already extracted from available QCD lattice data. DOI:10.1016/j.nuclphysa.2018.05.007

The main long-standing obstacle, how to deal with coupled-channel systems in the presence of anom-

alous thresholds, were overcome. A novel framework based on the concept of a generalized potential is established. DOI:10.1103/PhysRevD.98.076003

Depending on availability of computing and personnel resources, detailed predictions for the baryon resonance program at HADES and PANDA are now feasible.

Andreas Bauswein joined on July 2018 the theory department as leader of the research area "Relativistic Astrophysics". This area is funded by the ERC starting grant "Great Moves" and aims to develop innovative methods for the simulation of neutron star mergers and the analysis of their gravitational wave signal as well as the nucleosynthesis of heavy elements. The research is based on high-performance computing applications in close collaboration with experimental groups at the NUSTAR, CBM and HADES collaborations. He is also a personal investigator of the Collaborative Research Center 881 "The Milky Way System" at the Universität Heidelberg that during 2018 was renewed for its third funding period.





## 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 foster 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. such systems exhibit remarkable similarities, for example in the emergence of characteristic collective behaviour 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/M, U Heidelberg, U Münster, FIAS Frankfurt/M, 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)

### Selected publications of 2018

An EMMI Rapid Reaction Task Force Meeting on “Extraction of Heavy-Flavor Transport Coefficients in QCD Matter” was held in two parts in July and in December 2016. The participants continued to work on the studies initiated during the RRTF meeting throughout 2017 and published a joint report in 2018. The RRTF performed broadly based systematic investigations of the modelling components for open heavy-flavor diffusion and energy loss in strongly interacting matter in their application to heavy-flavor observables in high-energy heavy-ion collisions. Initial spectra including cold-nuclear-matter effects, a wide variety of space-time evolution models, heavy-flavor transport coefficients, and hadronization mechanisms were scrutinized in an effort to quantify pertinent uncertainties in the calculations of nuclear modification factors and elliptic flow of open heavy-flavor particles in nuclear collisions. Procedures were developed for error assessments and criteria for common model components to improve quantita-

tive estimates for the (low-momentum) heavy-flavor diffusion coefficient as a long-wavelength characteristic of QCD matter as a function of temperature, and for energy loss coefficients of high-momentum heavy-flavor particles.

- Rapp, R. ; Gossiaux, P. B. ; Andronic, A. ; et al.: **Extraction of heavy-flavor transport coefficients in QCD matter.** *Nuclear physics A* 979, 21 - 86 (2018) DOI:10.1016/j.nuclphysa.2018.09.002

Scientists from GSI and surrounding universities provide new insight into the formation of matter from analysis of particle production data taken by the ALICE experiment at the CERN LHC. The results reported in the Nature publication are also trail blazing for research at the future FAIR facility: especially the results on the production of light nuclei and hyper-nuclei open new perspectives for the CBM experiment at FAIR.

- Andronic, A. ; Braun-Munzinger, P. ; Redlich, K. ; et al.: **Decoding the phase structure of QCD via particle production at high energy.** *Nature* 561(7723), 321 - 330 (2018) DOI:10.1038/s41586-018-0491-6

## 8. Research of the department Experiment Electronics

Head: Dr. Caselle Michele, GSI  
 Author: Dr. Caselle Michele

The department Experiment Electronics (EEL) addresses the full spectrum of technologies relevant to detector instrumentation ranging from integrated front-end circuits, analog and digital electronics, detector control, data acquisition and data analysis. All research groups are guided by the requirements of demanding real-world applications. The long and well consolidated experience in the development of readout systems based on both FPGA-TDCs (Time to Digital Converter) and ASIC-TDCs, which have been successfully applied in time-of-flight and detectors for FAIR Phase-0 and STAR. Similarly, the EEL has a leadership role in the design of large dynamic range front-end readout ASICs for electromagnetic calorimeters, gaseous detectors and beam diagnostic instrumentation for FAIR.

Within the department, the matured experience in analog and digital readout electronics is tightly integrated with a well consolidated experience in design and commissioning of detector control, data acquisition and an analysis framework for experiments. The EEL is engaged to conceive and develop technologies for several experiments at FAIR and external international collaborations. In close collaboration with other GSI institutes and research groups, the EEL has a key responsibility in coordination, development, and production of electronics, control systems, and versatile data analysis frameworks. The department benefits of a consolidated international visibility and global reputation in the production and delivery of electronics and systems to external experiments in more than fifteen countries in the world, e.g. Xi'an Jiaotong University (China), Lund University (Sweden), Cracow University (Poland), etc.

### Projects in 2018

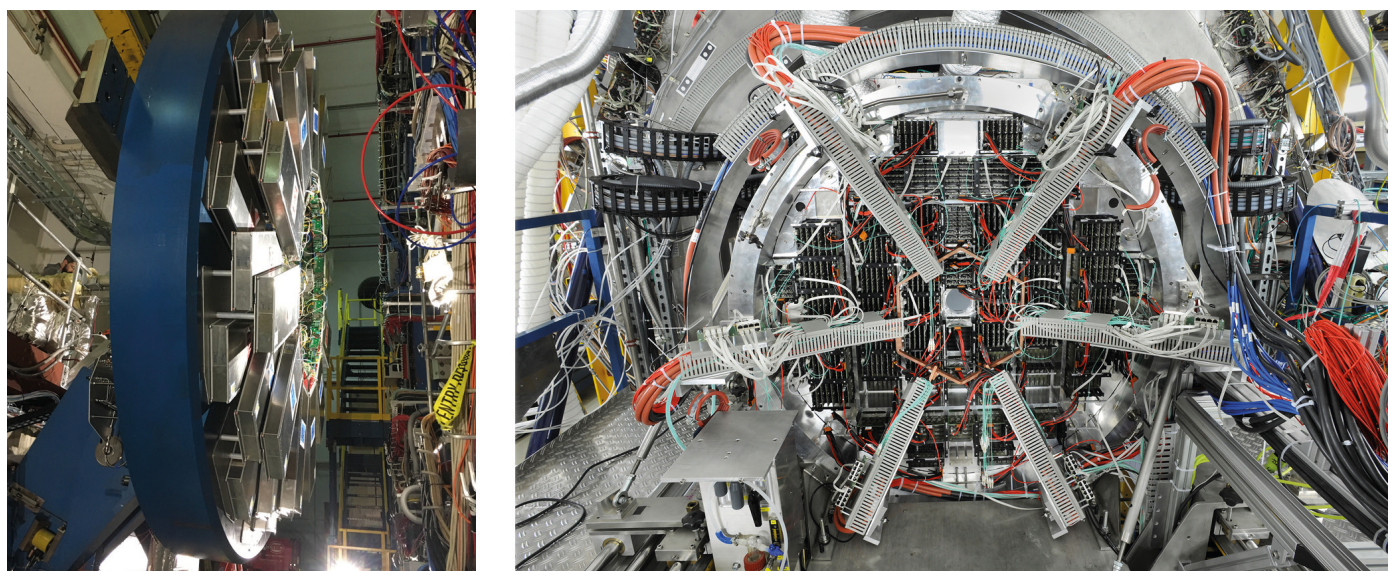


Figure 32. Readout cards installed at the eTOF (STAR) detector (a), at the RICH (HADES) detector (b)

The preparation of the electronics and system for the first FAIR Phase-0 production beamtime in 2019 was one of main focus of the activities in 2018. One of relevant activities was the installation of the readout electronics for the end-cap time-of-flight detector (eTOF) at the STAR detector for the RHIC program in 2019-2021, Figure 32 left). All 12 sectors were equipped by the 637 electronic cards designed and produced at the EEL. The readout system, currently in operation, is capable to readout the whole detector which features of 6912 channels of multi-gap resistive plate chamber (MRPC). Similarly, the readout and data acquisition system for the mCBM (SIS18) experiment has been successfully produced and installed

at the experimental area. The detectors consist of 800 channels for mTOF to be read out with a time precision below 80 ps. In close collaboration with the CBM and HADES experiments, the department was involved in the development and commissioning of the HADES Cherenkov photon detector (HADES-RICH). In 2018, all the necessary electronics for amplification, discrimination, precise time measurement and data-acquisition of the 28.000 channels and all necessary auxiliary electronics for data concentration, clock, trigger and power distributions was produced at the EEL and integrated into the HADES-RICH-detector, Figure 32 right). Additionally, the readout electronics for the new HADES-ECAL detector was produced and installed in 2018.

In collaboration between the GSI Beam Instrumentation (BEA) and the EEL department a 32 channel readout system for low-current profile measurements called POLAND (Profile Acquisition Digitiser) was developed in the last years. This electronic system is capable to read out beam diagnostic devices like Secondary Electron Monitor (SEM)-profile grids, Multi-Wire Proportional Chambers (MWPC), Ionisation Chambers or similar devices of the future FAIR accelerator system. Main part of the system is the current-to-frequency converter unit based on the QFW ASIC, the central logic unit based on an FPGA and an optical readout for data transfer to a host PC. After intensive tests the mass production for 350 units in the first batch has started in 2018.

The Multi Branch System (MBS), the data acquisition system at GSI, was strongly consolidated in 2018. In total, 160 MBS systems are currently in operation at many foreign laboratories and ten new MBS systems came in to operation 2018 at NUSTAR.

Turning detectors into a complete system is the leitmotif of the department. Control systems are essential to operate experiment detector setups and to automate teststands. The EEL supports EPICS and LabVIEW based systems by providing infrastructure, consulting, support, dedicated framework development and maintenance. Furthermore, the EEL is involved in the development of concrete controls applications from prototyping to large scale distributed systems, e.g. CBM, HADES, PHELIX, SHIPTRAP, TASCA, and some others.

## Outlook for 2019

One focus will be the test and characterisation of several ASICs which have been designed and produced during 2018. Other new ASIC developments are foreseen to be used for gaseous detector front-end readout for GEM-TPC detector at Super-FRS and GEM tracker at PANDA.

It is planned to design, implement and release several variants of FPGA-TDCs architectures targeted on Lattice FPGA family with channel numbers ranging from 32 to 64. All designs are based on newly developed methods and algorithms, some of which have already been tested successfully. Target platforms are TRB3, TRB3sc, TRB5sc, TAMEX, DiRICH and MDC. In strong collaboration with IT department is the improvement and consolidation of the LTSM long-term storage system for HADES experiment.

The HADES magnet control system will be migrated to EPICS. It is planned to migrate the CS framework based SHIPTRAP control system to CS++, to refactor the rudimentary LabVIEW system of the laser spectroscopy experiment behind SHIPTRAP to CS++, and to build a new CS++ project for the FSR Ion Catcher.



## 9. Research of the department Target Laboratory

Head: Dr. Bettina Lommel, GSI

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

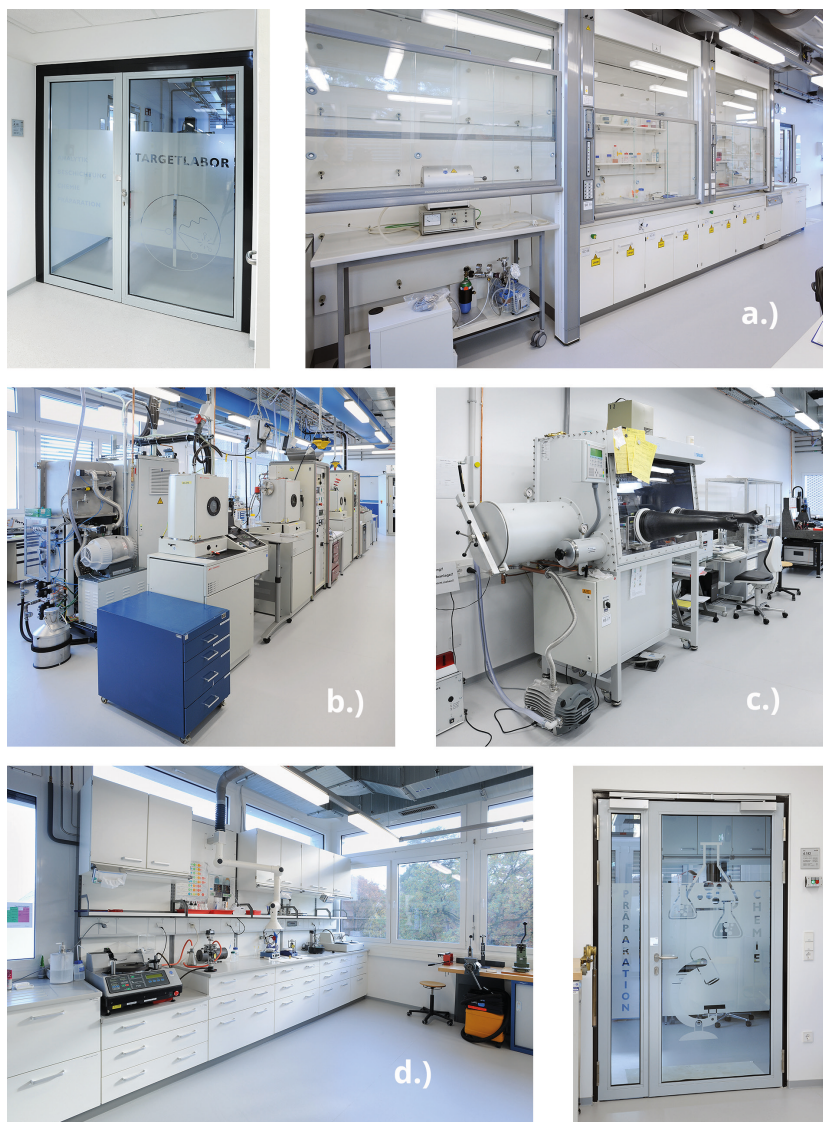


Figure 33. Photographs of the newly renovated Target Laboratory (photographs by G. Otto/GSI). For information follow the text.

2017/2018 the Target Laboratory moved to a new site in one of the already renovated parts of the GSI buildings since the old area has to be cored and refurbished. Most of the security-relevant installations like fume hoods, cupboards for acids, bases, solvents and gases, etc. had to be replaced. In the picture above the new fume hoods (Figure 33, a.) including a walk-in hood for different furnace set-ups is shown. The technical building equipment was totally renewed and adapted to the specific technical needs for the different room zones: In the zone, "coating" all box coaters are installed allowing one person to control more than one machine in parallel (b). In the zone, "analytics" an inert-gas glove box, microscopes, a SEM and other analytical equipment are mounted (c). Finally, in the zone "chemistry and preparation" lapping and polishing equipment is situated together with the fume hoods, several furnaces and storage room for chemicals and accessories (d). Since April 2018, the target laboratory is back to full operation. With this state of the art installation the new laboratory is ready to meet the future challenges of GSI and FAIR.



## 10. Research of the Department IT

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

The IT department develops and maintains common scientific software for the physics experiments in close collaboration with the experimental groups and external institutes (e.g. CERN and JINR Dubna). In addition, several members of the IT department have direct responsibilities in the software projects of the FAIR experiments. The IT is involved in developing software and using cutting edge technologies for different experiments [P. Cabanelas et al., EnsarRoot: The framework for simulation and data analysis for ENSAR, 2018, J. Phys.: Conf. Ser. 1024 012038, DOI:10.1088/1742-6596/1024/1/012038; M. Al-Turany et al, ALFA: The new ALICE-FAIR software framework, 2015, J. Phys.: Conf. Ser. 664 072001, DOI:10.1088/1742-6596/664/7/072001] (e.g. ALICE, CBM, PANDA and R<sup>3</sup>B) and even different communities [T. Heller, et al. "Harnessing Billions of Tasks for a Scalable Portable Hydrodynamic Simulation of the Merger of Two Stars." The International Journal of High Performance Computing Applications, Feb. 2019, DOI:10.1177/1094342018819744].

In anticipation of high data rates in next-generation, trigger-less FAIR and LHC RUN3 ALICE experiments, the FairMQ library [<https://github.com/FairRootGroup/FairMQ>] is developed in the ALFA software framework [M. Al-Turany et al, ALFA: The new ALICE-FAIR software framework, 2015, J. Phys.: Conf. Ser. 664 072001, DOI:10.1088/1742-6596/664/7/072001]. FairMQ supports a data-flow driven computing model by providing building blocks to construct distributed processing pipelines. FairMQ offers multiple implementations of its abstract data transport interface in order to integrate existing data transport technologies. Moreover, it provides efficient intra-node transports (shared memory [5]) and meanwhile an efficient inter-node transport (RDMA D. Klein et al. "RDMA-accelerated Transport for ALFA" accepted for publication, 2019, J. Phys.: Conf. Ser.) based on libfabric [OpenFabrics Interfaces libfabric, <https://ofiwg.github.io/libfabric/>]. With multi-processing, each process assumes limited communication and reliance on other processes. However, the communication between the different processes have to be controlled and orchestrated, e.g.: A reconstruction task is represented now by a few processes that consist out of a processing graph (topology) which could run on one or more nodes. To manage such an environment, the Dynamic Deployment System (DDS), DDS is developed as an independent set of utilities and interfaces, providing a dynamic distribution of different user processes for any given topology on any Resource Management System (RMS) or a laptop. [A. Lebedev et al. „DDS: The Dynamic Deployment System " accepted for publication, 2019, J. Phys.: Conf. Ser.]

In preparation for new experiments and their demanding requirements a first Analysis Facility prototype was built in order to prepare the conversion and expansion of the current ALICE Tier2 center. Within this context an XRootD plug-in was developed that significantly improves the Input/Output performance of local file operations [J. Knedlik et.al. "XRootD plug-in based solutions for site specific requirements" accepted for publication, 2019, J. Phys.: Conf. Ser.].

The Vc library is being developed for researching data-parallel types and as a solution for explicitly data-parallel programming [M. Kretz, Vc Library, <https://github.com/VcDevel/Vc>]. Meanwhile, Vc has become an important building block in the high energy physics community. Their reliance on Vc shows that the library and its interfaces were developed to production quality. The next step will be to standardize (ISO) and implement the data parallel programming types based on Vc for the standard C++ library. A proposal based on Vc is making progress in the C++ committee.

### Selected publication of 2018

- Cabanelas, P. ; Alvarez-Pol, H. ; Galiana, E. ; et al.: **EnsarRoot: The framework for simulation and data analysis for ENSAR**, FAIR NExt generation ScientistS 2017, FAIRNESS 2017, Sitges, Spain, 28 May 2017 - 3 Jun 2017 *Journal of physics / Conference Series Conference Series* 1024, 012038 (2018) DOI:10.1088/1742-6596/1024/1/012038





## 11. Promoting early career researchers

### 11.1 38<sup>th</sup> Summer Student Program at GSI

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



Figure 34. Participants from the 38th summer student program at GSI. Photograph by G. Otto/GSI.

For our 38<sup>th</sup> summer student program we were welcoming 36 students on the last-year Bachelor- or Master-study level. The students came from 24 different countries mostly from Europe with special focus on students from the Balkan states, and furthermore a few students from Middle, South and East Asia, South Africa and Middle America.

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 provided a survey over the various research fields and applications at GSI/FAIR including a special Summer Colloquium on a GSI/FAIR related topic. The program was supplemented by introductory soft skill courses. During the final week the summer students organized a seminar, where each participant reported 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, which that year the Summer Student team was winning. Every summer student obtained a report book as a souvenir on the eight summer weeks shared at our research center.

Further details can found on our web-pages: <https://theory.gsi.de/stud-pro/> and <https://www.hgs-hire.de/summer-program/>



## 11.2 Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe for FAIR)

Authors: Dr. Henner Büsching, Goethe University Frankfurt/M ; Dr. Gerhard Burau, FIAS & Goethe University Frankfurt/M

The HGS-HIRe Graduate Day in October 2018 celebrated the 10<sup>th</sup> anniversary of the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe for FAIR). The broad range of doctoral projects conducted by participants of the graduate school was reflected by a variety of scientific talks presented by the participants of HGS-HIRe. A plenary talk by Prof. Mei Bai (GSI/FAIR) on “The Challenging FAIR Project” complemented the scientific program of the event.



Figure 35. Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe for FAIR). Photographs by Henner Büsching and Gerhard Burau.

Supported by the Initiative and Networking Fund of the Helmholtz Association, the Helmholtz Graduate School HGS-HIRe for FAIR has been established in October 2008 as a joint endeavour of the GSI Helmholtzzentrum für Schwerionenforschung together with the Frankfurt Institute for Advanced Studies (FIAS) and the universities in Darmstadt, Frankfurt/M, Gießen, Heidelberg and Mainz to promote and support structured doctoral training for young researchers associated with GSI and the Facility for Antiproton and Ion Research FAIR. After a very positive evaluation by the Helmholtz Association, especially appreciating the program elements and the spirit of the graduate school and everyone involved, GSI/FAIR agreed on

a sustainable funding of HGS-HIRe in 2015.

More than 340 doctoral students scientifically related to the GSI/FAIR research pillars APPA, CBM, PANDA, and NUSTAR are participating in the program of HGS-HIRe (by 12/2018). Similarly impressive is the number of 446 participants who finished their doctoral thesis so far and became alumni of the graduate school. 43 of them graduated in the year 2018. Altogether more than 240 participants and alumni (> 30%) are of international origin. The great popularity of HGS-HIRe allows for a consequent realization and development of the structured doctoral program.

An essential pillar of the HGS-HIRe structure is the doctoral training program. Numerous events on various topics, addressing both scientific and non-scientific (transferable skills) training, have been organized in 2018 including six lecture and power weeks and a total of eight transferable skills courses. Special events, as the HGS-HIRe Graduate Day, Perspectives events to facilitate the career planning of the participants after the doctoral project, and the HGS-HIRe Summer Student Program at GSI with 36 participating students from 24 countries complemented the educational program of HGS-HIRe in 2018.

The HGS-HIRe scientific travel program for participants consists of individual travel budgets for the doctoral students to attend conferences or workshops and the HGS-HIRe Abroad program offering participants a number of grants, awarded in a competitive process several times per year, for a one to three months research stay abroad to facilitate their thesis project and to intensify research collaborations.

Furthermore, the graduate school serves, strongly supported by FIAS, as the central contact and care centre for the participants, their supervisors and the partner institutions. Administrative and social aspects handled include the administration of the individual HGS-HIRe PhD committees, help with student status issues and visa/residence permits. In addition, HGS-HIRe centrally supports the organization as well as administration of the doctoral funding programs of GSI and HIC for FAIR.

Finally, HGS-HIRe continued its public outreach activities with strong involvement of the participants, particularly the Primary School Program in collaboration with the Polytechnische Gesellschaft Frankfurt and the National and International Masterclass Program within the BMBF-initiative "Netzwerk Teilchenphysik".



## 11.3 GET\_INvolved Programme

Dr. Pradeep Ghosh, FAIR

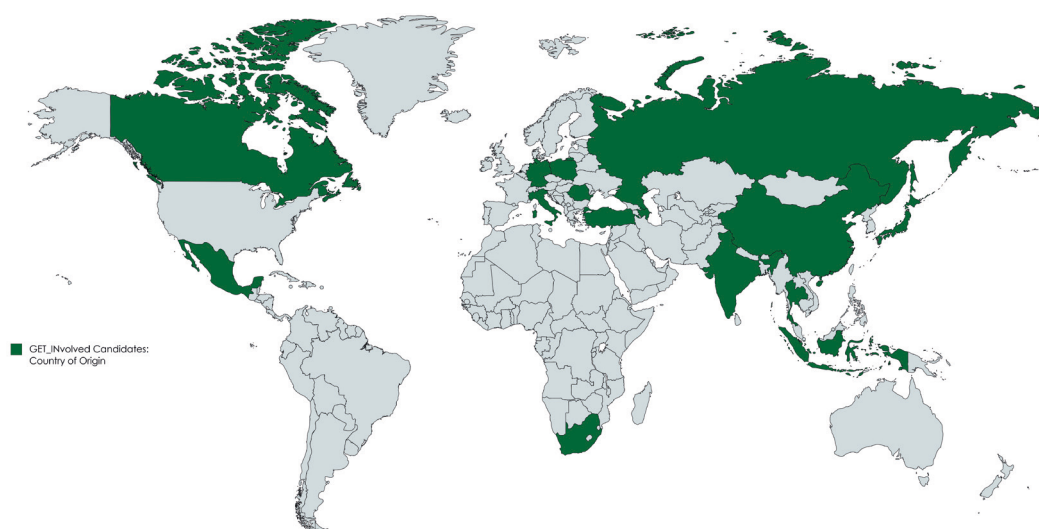


Figure 36. Countries marked green represent the country of origin of talents participating in the GET\_INvolved Programme (Credit: Map created with Mapchart.net are licensed under CC BY-SA 4.0.)

The GET\_INvolved Programme has been invited international students and early stage researchers with opportunities to perform internships (practical experience) and get early research experience in the GSI and FAIR.

### Outreach and Status

More than 30 candidates have been accepted to benefit from the GET\_INvolved Programme. This includes individual student internships and research experience and candidates from dedicated bilateral/multilateral programmes as well. The spectrum ranges from students to postdoctoral researchers. The distribution is shown in Figure 37.

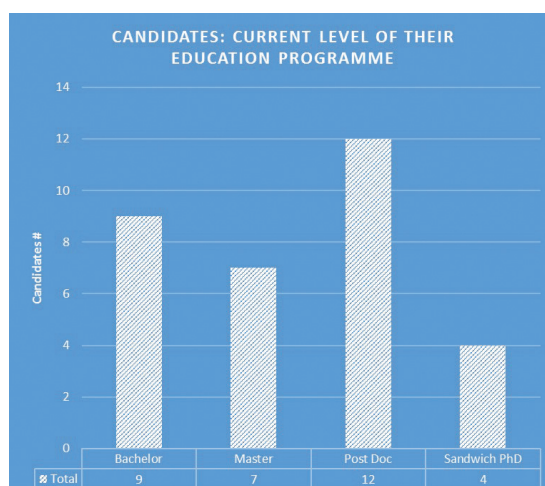


Figure 37. Talents benefited through the programme and their educational level.

Until the end of 2018, the programme has attracted partners to sponsor young talented students and researchers from their institutes to benefit from the GET\_INvolved Programme.

### Potential new partners

Negotiations with following partners

- Warsaw University of Technology, Warsaw Poland and Bucharest University Romania (ERASMUS+ framework),
- the Suranaree University of Thailand, Bangkok Thailand, South African Institute iThemba Labs and the Mody University of Science and Technology, Laxmangarh India

are ongoing to participate with a framework or bilateral agreement focused on internship and research mobility under GET\_INvolved Programme.

The opportunities for aspirants within the framework of the GET\_INvolved Programme are now available online through our webpage [www.fair-center.eu/get\\_involved](http://www.fair-center.eu/get_involved).

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

Head: Jörg Blaurock, GSI

Authors: Emmanuel Rosi and Mandy Raponi, GSI

On the FAIR construction site, the excavation works in area north are ongoing as planned. The contractor of the excavation pits in area north (company ARGE) has handed over the first pit (pit-1) to the main contractor of the building shell north (company PORR). Moreover, the first part of the second pit (pit-2) was handed over to company PORR at the end of August 2018. The dewatering and excavation works for third, fourth, fifth, sixth and seventh pits have been performed as planned.

The main contractor of the building shell north (company PORR) has successfully poured the first section of the 2 meters thick ground slab in the first section of the excavation pit-1 of the SIS100 Tunnel. With this successful achievement, the FAIR project reached on the beginning of August 2018 a major milestone. Thus, the construction work of the building shell north is moving forward as planned.

Further construction activities in term of site management, site logistic and temporary site infrastructure installations are progressing according to the plan. In this regard, it is to be mentioned that the FAIR site management and construction management teams have moved to the site offices at the end of July 2018. FAIR site offices and meetings rooms are essential for the proper coordination of and communication with all contractors.

The FAIR transformer station north was put into operation in February 2018 and the transformer station south started operation on 28<sup>th</sup> June 2018 on the construction site of the future FAIR accelerator facility as planned. These are the first FAIR sub-systems, which are in operation on the FAIR construction site.

The completion of the GSI connection to FAIR (GAF) project was also a major milestone reached in time. This allowed the start of the FAIR experimental Phase-0 in summer 2018.

The GAF project consists mainly of the upgrade of the radiation protection of the existing SIS18 area and building a tunnel section, by which the FAIR accelerators will be connected to GSI. The GAF and the WTK project could be completed up to a level allowing beam operation. Some of the new technical infrastructures required for the FAIR high repetition and high intensity operation, such as the management system for radioactive air, the new fire prevention system and others, will be completed after the present beam run.

In terms of tendering and award processes, within the last six months the "elevators" contract was awarded to the company "Thoma Aufzüge GmbH" and the tendering for the civil execution packages "Construction area south" has been published at European level early September 2018.

On the Accelerator side significant progress and milestone achievements can also be reported such as; The delivery of 20 High Energy Beam Transport (HEBT) vacuum chambers from BINP; The delivery of the 21<sup>st</sup> and the production of the 33<sup>rd</sup> SIS100 dipole magnets manufactured by BNG (Würzburg, Germany); The production of the 2nd of series RF cavity and power supply unit for the Collector Ring; The delivery of two First of Series quadrupole units by JINR; The successfully completed copper plating of the RFQ tank for pLinac as well as the first delivery of 6 series power converters from India for HEBT.

The experiments have progressed steadily in all areas. The FAIR Phase-0 experiments at GSI have started in July 2018 as planned. However, due to technical issues with the newly installed ventilation system in the GSI facility the current beam time could not continue as planned and the beam time was shifted to the beginning of 2019. The definition of FAIR Day-1 configuration is now frozen and was presented during the 10<sup>th</sup> meeting of the Expert Committee Experiments (ECE) on 9<sup>th</sup>-10<sup>th</sup> October 2018. The new experiment baseline is integrated into the overall FAIR Project baseline.

The major focus for the next six months can be summarized as follows:

In the area of civil construction, the major and most visible site activities will be the continuation of civil works for the SIS100 tunnel, the start of the building shell construction work in the second excavation pit and the start of the construction work in building (H0705A "G004").

In the area of the Accelerator, further essential contracts are foreseen to be closed like the contract for the radiation resistant dipoles, quadrupoles and sextupoles, ToF detectors, and beam diagnostic detectors with Russian institutes. The 3<sup>rd</sup> power converter as well as power cables and Super FRS beam catcher contracts were contracted with India. Beam diagnostic detectors with Finnish and Swedish Institutions. Local Cryogenic equipment for SIS100 and Super FRS with Polish Institutions. The large tender for the main cryogenic plant (in-kind GSI) has been launched in the market in Q1/2018 and is envisaged to be awarded depending on the market response/tendering process.

The contract for SIS100 quadrupole unit testing (in-kind GSI) in Dubna, the collaboration contract for the SIS100 quadrupole module testing (in-kind GSI) in Salerno are still in preparation.



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

Head: Dr. Peter Spiller, GSI

### SIS18 Status Report

After two years shut down, the re-commissioning of SIS18 could be performed on June 19<sup>th</sup> as scheduled. Only two days after the start of beam commissioning, an Argon beam could be accelerated and extracted. Beside major technical upgrades and a significant modification of the accelerator building, the implementation of the new FAIR controls system created the biggest challenge. Although, as expected, minor bugs are still to be fixed, SIS18 is available for the planned user operation.



Figure 38. The three new MA loaded Rf acceleration cavities installed in SIS18. The cavity will allow acceleration of low charge state heavy ions (e.g.  $U^{28+}$ ) with maximum ramp rate.

The new RF acceleration cavities (see Figure 38) could be tested with high energy beam transport (HEBT) and were available for the user operation in September 2018. Some of the last components of the SIS18 upgrade program, could not be installed before the commissioning. A delay in manufacturing of the vacuum chamber inhibited the installation of the new bipolar dipole magnet in the HEBT system. The power converter for this magnet has been delivered by JAEGER. Also the ionisation profile monitor (IPM) and the new microspill cavity could not be installed due to missing UHV components. All components, including a new transfer channel TK chopper system, were installed in the shutdown end of 2018.

To mitigate the misalignment of SIS18 due to ground water lowering, all components have been aligned on a tilted plane. This assures a smooth transition from SIS18 to the HEBT system and provides minimum effort in terms of repositioning of misaligned components.

## SIS100 status report

The series production of the SIS100 superconducting dipole magnets has been continued. Meanwhile, 21 cryogenic modules containing the superconducting dipole magnets have been manufactured at BNG (Würzburg, Germany) and delivered to GSI. Further 12 modules have passed the factory acceptance test (FAT) and are temporarily stored at BNG. Some corrective measures had to be implemented in terms of geometrical precision of interfaces and the hydraulic adjustment of the cooling circuits. The high quality achieved with respect to the magnetic properties, the geometrical precision of the magnet yoke and the measured magnetic field quality, could be reproduced over the so far completed series.

Two first of series (FOS) quadrupole units manufactured at JINR Dubna (Russia), comprising two superconducting quadrupole magnets, a superconducting steerer and a sextupole magnet, have been delivered to GSI. The units were directly transferred to BNG for integration into the FOS quadrupole module. The manufacturing of parts for the FOS quadrupole module has been launched at BNG. The synchronization of the different work packages for a provision of all parts required for integration of the modules, in time and schedule is a major challenge.

In parallel, the negotiations with INFN and the University of Salerno have been continued. The program of module testing at Salerno has been fixed and the design for the adaptation of the local cryogenic-facility has been completed.



Figure 39. Resonance sextupole magnets manufactured at DANFYSIK

All resonance sextupole magnets have been produced at DANFYSIK and delivered to GSI.

The Factory Site Acceptance (FAT) test and Site Acceptance Test (SAT) of the FOS acceleration cavity, manufactured and commissioned at RI (Research Instruments), has been finalized successfully. The procurement of components for the series production has started by the contractor.

In parallel to the acceleration cavities, the series of bunch compression cavities is manufactured at AURION (Seligenstadt, Germany). Seven of nine bunch compression cavities have been manufactured and accepted. With a major delay, the OCEM (Bologna, Italy) power converter, required for the power tests of the cavities, is presently set-up at AURION.

Both main injection devices, the injection kicker system and the injection septum magnets will be designed and manufactured by Danfysik (Taastrup, Denmark). After the Final Design Report (FDR), the procurement of components for the kicker system has already been launched. As first device of the extraction system, the electrostatic septum has also been awarded to DANFYSIK.

The issue with the cooling of the cryogenic dipole magnets has been solved. The negligible distortion of the magnetic field, combined with the excellent intrinsic magnetic field quality of the produced dipole magnets, enable the direct soldering of the cooling pipes into the ribs of the chambers. Thus, with technical decision, the series production of the dipole chambers can be released without technical risk. In parallel, to the dipole chambers, two FOS quadrupole chambers have been ordered.

Several other components of SIS100 are in the procurement process or have been contracted already, e.g. the standard pumping chambers, low-level electronics equipment for RF systems and the fast quadrupole magnet.

## 12.2 Research & developments of the division Super Fragment Separator

Head: Dr. Haik Simon, GSI

The Low-Energy Branch spectrometer is suggested to be realized with full performance from the beginning, also in order to avoid extra costs related to the staging. The additional costs for the full version of the Low Energy Branch amounts to 3.8 M€ (2005 prices).



Figure 40. Testing facility at CERN for the SAT of super FRS SC magnets

The facility was ready for operation in 2018. The SAT of the FOS multiplet will start with its delivery to CERN. The completion of the FOS (originally planned for June 2018) had to be shifted to September 2018 due to a production problem related to the outer shell of quadrupoles, the problem with the supplier of the shell is meanwhile solved and the subsequent production is running on track.



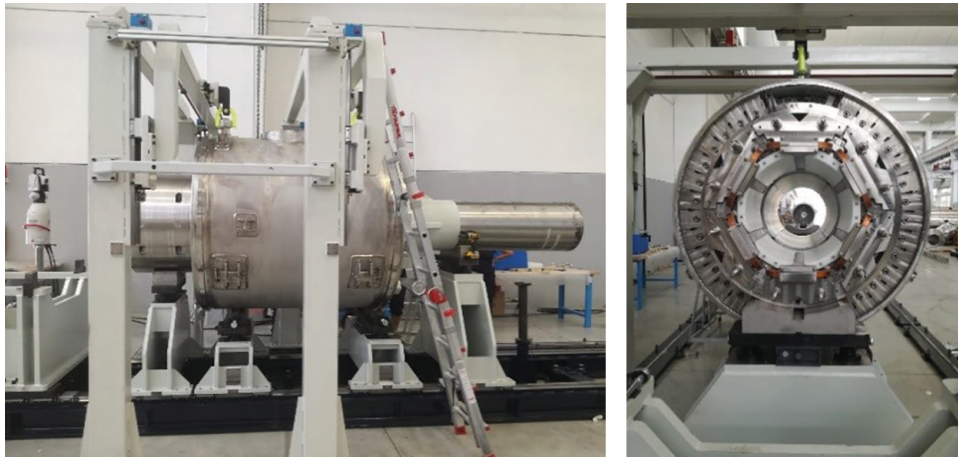


Figure 41. Fabrication of the FOS short SC multiplet (ASG, Genoa, Italy)

The design of the standard superconducting dipoles is progressing as expected. The conceptional design (Figure 42 left) was reached in May 2018. The Design Readiness Review was achieved too; the documents with main parameters were verified and accepted; in particular, the stray field impact of the large aperture magnets being one of the expected technical risks has been evaluated.

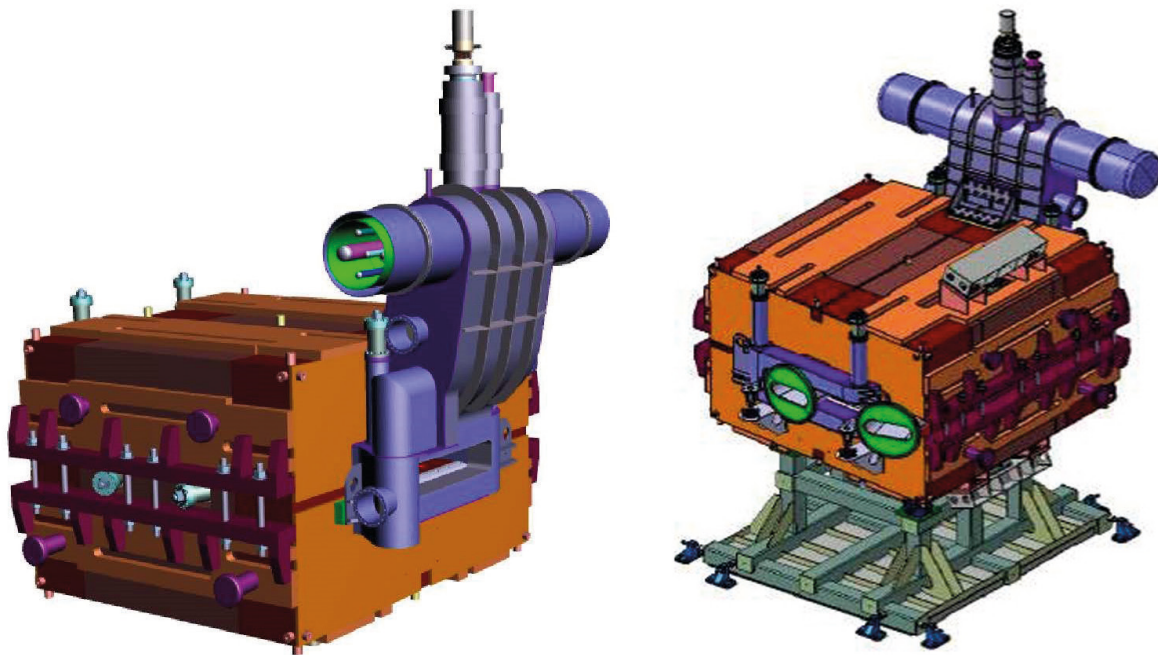


Figure 42. Left: Technical design of the Super FRS standard superconducting dipole. Right: Technical design of the Super FRS branched superconducting dipoles

The detailed technical design of the SC branched dipoles is currently progressing at CEA, France (Figure 42 right). On June 15<sup>th</sup>, a successful meeting with the French colleagues yielded consent on key technical aspects of the component.

The works on the layout of the local cryogenic systems in order to achieve a simplified modular design have been continued. Together with the polish colleagues from Wrocław University of Science and Technology (WUST), our in-kind partner for the design, production, and installation of local cryogenics, the scheme for its realization has been further developed and issues concerning scope and value of the package are addressed.



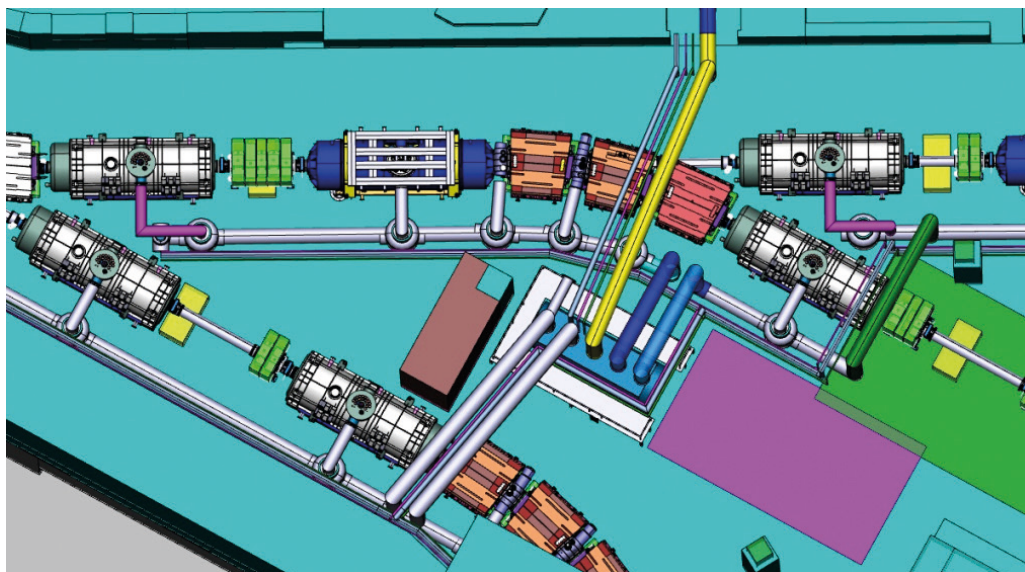


Figure 43. Upgraded layout of the Local Cryogenic System, following suggestions of the Polish in-kind partner.

A simplified and very cost-effective solution for the quench detection system (QID) is adopted. The quenching-detection prototype system is ready to be tested. The prototype is based on the new concept, according to which the Q/D will be integrated in the power converter. As well as for the adaptive control unit (ACU) and DC current transformers (DCCT), which are German in-kind too, the Q/D board has to be integrated in the cabinet by the Indian in-kind provider. The potential scope for Indian power converter in-kind is outlined, detailed proposal in preparation by the In-Kind office.

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

Head: Dr. Klaus Knie, GSI

The simplification of the interface to the GAF project allows a more economical and faster installation. The pLinac beam dump area and the shielding wedge between pLinac and SIS18 are completed as part of the GAF project. As a consequence, civil construction activities for the pLinac building without interfering with the GSI operation are possible now.

The commissioning of the proton source built at CEA is in progress. The design ion current of 100 mA has been produced. The construction of the low energy beam transport (LEBT) is in progress.

The contract with our French collaborators from CNRS has been signed. All seven Klystrons provided by CNRS passed the FAT successfully and have been delivered to GSI. SAT A is completed. The in-house production of the first-of-series modulator is in progress. End-to-end beam dynamic simulations from ion source to SIS18 injection have been completed. Error simulations for the internal quadrupoles have been completed. After the very successful power RF tests of the ladder RFQ prototype the design of the full size RFQ, done at IAP Frankfurt is completed and the production is close to completion. Copper plating of all parts of the RFQ tank is completed.

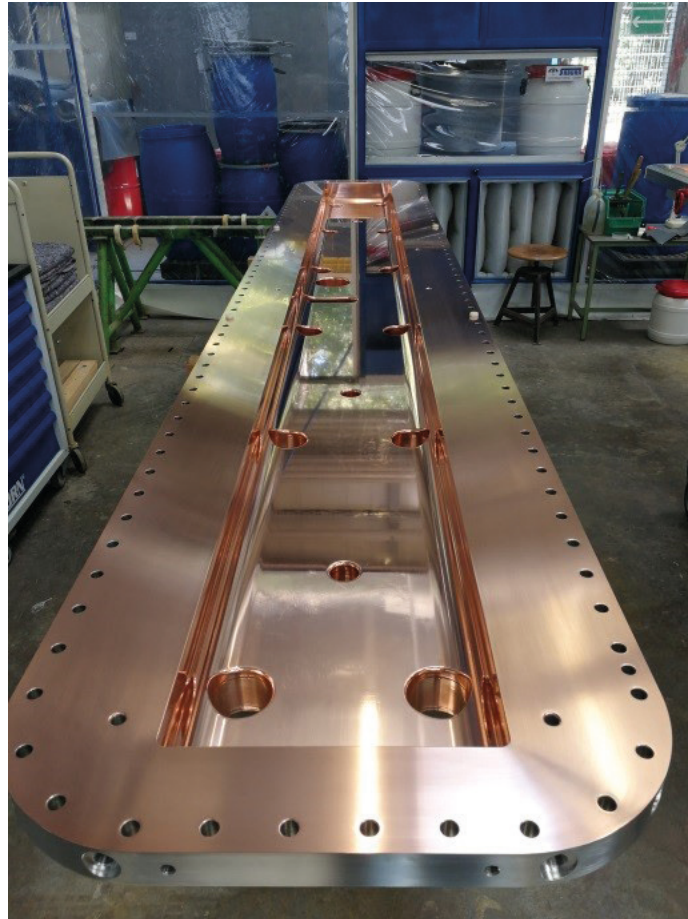


Figure 44. Lower part of the RFQ tank after successful copper plating

The layout of the CH and CCH cavities is finished. Tests of the copper plating and welding procedures have been started with simplified dummies of the most demanding CH structures. The production of the internal quadrupole triplets is ongoing. The specifications of the 15 beam profile monitors have been completed and the procurement process has been started.

### p-bar Target

For the magnetic horn system a design study in collaboration with an industrial partner, started in February 2018, is progressing.

ANSYS simulations for target, collimators and beam dumps (for HEBT and APPA dumps as well) are in progress. An experiment at the HiRadMat facility at CERN has been performed in order to test the mechanical stability of different materials for the p-bar target and to do a benchmarking of our simulations. Data analysis is in progress.

## 12.4 Research & developments for the collector ring of the FAIR Project

Heads: Dr. Ivan Koop/Budker Institute, Dr. Oleksiy Dolinsky/GSI

The "Rest of CR" contract with BINP on the production of CR components and amendment to HOAI contract have been signed on 26<sup>th</sup> June. Work on the remaining specs preparation is ongoing. Major part of the specifications has been already approved.

CDR for the dipole magnet has been performed in April 2018. At the same time, the production planning and preparation is ongoing as planned.

FAT tests of the second Power Supply for Collector Ring debuncher have been successfully done. The series production of RF debunchers is ongoing.

FAT/SAT of the FoS CR stochastic cooling power amplifier has been done. The system works according to specification and it is reliable.

The Palmer Pick-Up specification is ready. Engineering activities for the pick-up tank and RF signal processing of the stochastic cooling system is ongoing.

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

Head: Dr. Dieter Prasuhn, HESR

The components with the longest delivery time for the HESR, dipoles and quadrupoles were delivered completely to Jülich and technically approved. 30 of the dipole magnets were pre-assembled in Jülich with vacuum chambers and delivered to Darmstadt for interim storage.

All other essential components are in production or series production and most of them will be delivered to Jülich by the end of 2019. After pre-assembly, these components will also be fully transported to Darmstadt. The first installation window for the HESR tunnel is scheduled by FSB for a few months in the first half of 2022. The legal release of the HESR building for usage is presently scheduled by FSB for December 2022. At that time the installation of HESR can be completed and commissioning can start.



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

Head: Dr. Stefan Menke, GSI

The sub-project Commons takes the responsibility for the major technical systems according the Work Breakdown Structure (WBS) :

### High Energy Beam Transport (HEBT)

Magnets:

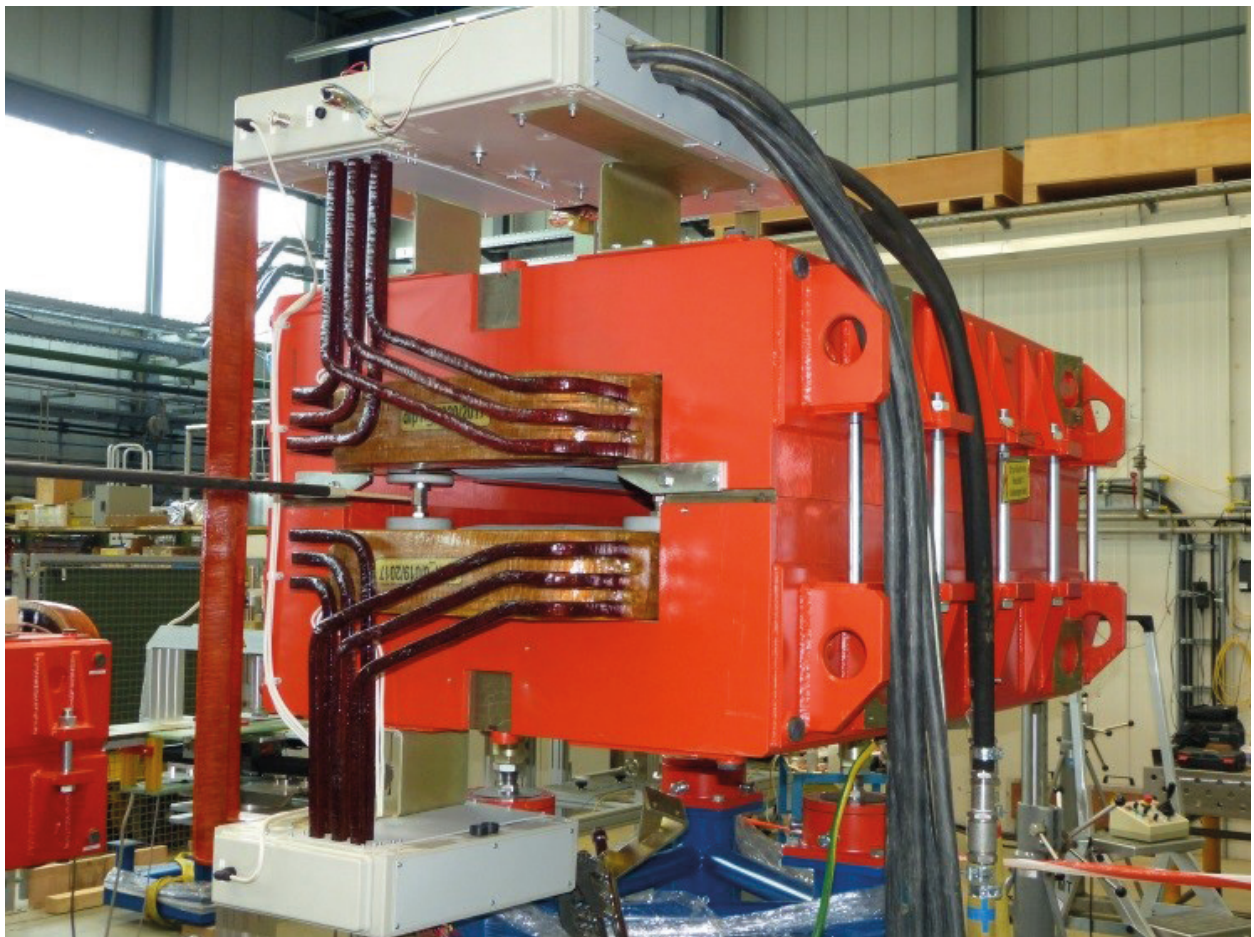


Figure 45. Vertically deflecting dip1f\_0 during magnetic measurements in horizontal position at GSI.

Series production of batch1 (51 dipole magnets) is running in full scale at Efremov Institute of Electrophysical Apparatus in St. Petersburg, Russia (NIIEFA). In the first half of 2018 two more series magnets of type dip13\_0 and the first two vertically deflecting magnets of type dip1f\_0 were delivered to FAIR/GSI, see Figure 45.

In total there are now 18 dipole magnets of batch1 on GSI/FAIR site.





Figure 46. Quadrupole magnet quad2 and steering magnets s100h/v at BINP.

The magnets of batch2 and 3 (22 dipole, 166 quadrupole, 92 steerer magnets) will be built by the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia. The pre-series magnets of the standard 18Tm quadrupole magnet type quad2 and the 100Tm steering magnet type s100h/v passed successfully the Factory Acceptance Test (FAT) at BINP in March 2018, see Figure 46.



Figure 47. Yoke half of dipole magnet dip15\_0.

The pre-series steering magnets of type s100h/v were shipped to GSI/FAIR in July 2018 for the upcoming Site Acceptance Test SAT, while the pre-series quadrupole magnet of type quad2 stayed at BINP for commissioning the new magnetic measurement system for quadrupole magnets, which was recently

successfully completed. For dipole magnet type dip15\_0, quadrupole magnet type quad11 and steering magnet type s18 production of yokes and coils has already started, see Figure 47, while the left magnet types are now in the final design phase.

### 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 two contracts between FAIR, the Indian shareholder BOSE institute and the provider ECIL comprising in total 196 power converters for HEBT (152 for quadrupole and 44 for steering magnets) are closed.

In spring 2018 a series of 6 quadrupole power converters were manufactured and passed the FAT (Factory Acceptance Test) successfully. GSI/FAIR witnessed the manufacturing and testing process. These power converters were delivered in August 2018 to GSI/FAIR.

The delivery of the series production for another 67 quadrupole power converters of the same type is expected in August 2019.

### Beam Instrumentation:

After completion of FAT tests the series production of 25 vacuum chambers with ceramic gap for RT/FCT has started at FMB Feinwerk- und Meßtechnik GmbH. Production and Tests of the full series will be completed in 2018.

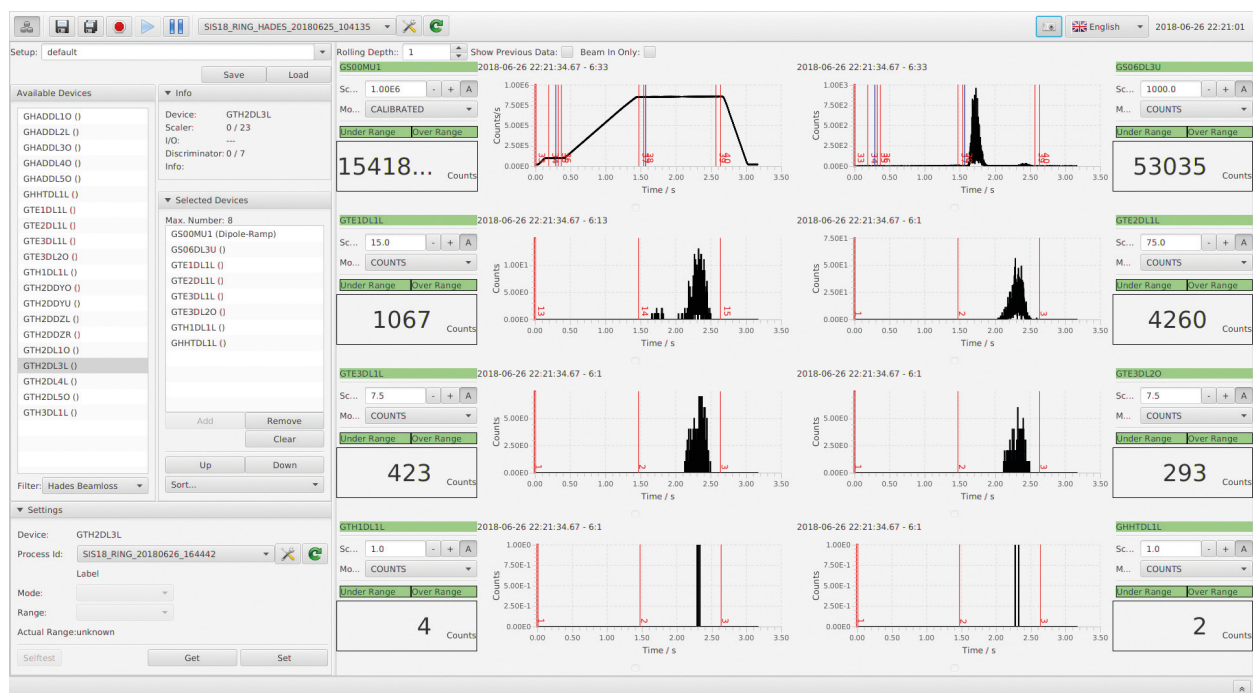


Figure 48. LASSIE screenshot with beam at HADES beam line from June, 26th 2018, measurement of FAIR-type beam loss monitors.

Moreover, the work on data acquisition and expert control applications for beam diagnostics is well in progress. In compliance with the specified form factors for beam instrumentation data acquisition systems (DAQ) at FAIR, first HEBT DAQ systems were successfully commissioned at the existing GSI HEST beam lines with beam. For example, the LASSIE system (Large Analog Signal and Scaling Information Environment) is based on the state-of-the-art MTCA.4 SIS8800 Multi-Purpose-Scaler and SIS8980 LE Discriminator (as Rear Transition Module RTM) from company Struck GmbH. The scaler modules count

all signals from any type of beam instrumentation particle detectors, such as plastic scintillators, beam loss monitors, ionization chambers or secondary electron monitors along the beam line. These intensity measurements are essential for the control of beam parameters, especially during beam transport to a target or physics experiment. The FESA/JavaFX based software set depicted in Figure 48 allows for many different types of measurements and data visualization.



Figure 49. CUPID DAQ system: 6-Slot MTCA.4 setup with White Rabbit timing receiver (FTRN-AMC) and 8-Channel GbE Switch AM217 from Vadatech for GbE camera readout

With the CUPID system (Control Unit for Profile and Image Data) another FAIR type DAQ system was successfully tested. CUPID will be used to measure beam profiles on scintillating screens by video imaging with Gigabit Ethernet cameras. The system can host 8 GbE cameras per modular switch (Vadatech AM217). Here, the  $\mu$ TCA form factor was chosen as it provides for very high data bandwidth on its backplane, see Figure 49. Video imaging systems may create a huge amount of data, which can easily be handled on such a platform. Both systems, LASSIE and CUPID, make use of the FAIR Timing Receiver Node (FTRN), which was developed in 2017/18 as an In-kind contribution by Cosylab, Slovenia. In combination with the White Rabbit timing system a precise triggering and measurement is guaranteed.

Furthermore, the cooperation with all Slovenian in-kind providers is very successful. For the sub-projects HEBT BPM DAQ and BPM pre-amplifier (Instrumentation Technologies) all hardware components were delivered to GSI, detailed site acceptance tests of the electronics are ongoing and performance tests are very successful so far.



## Vacuum chambers:

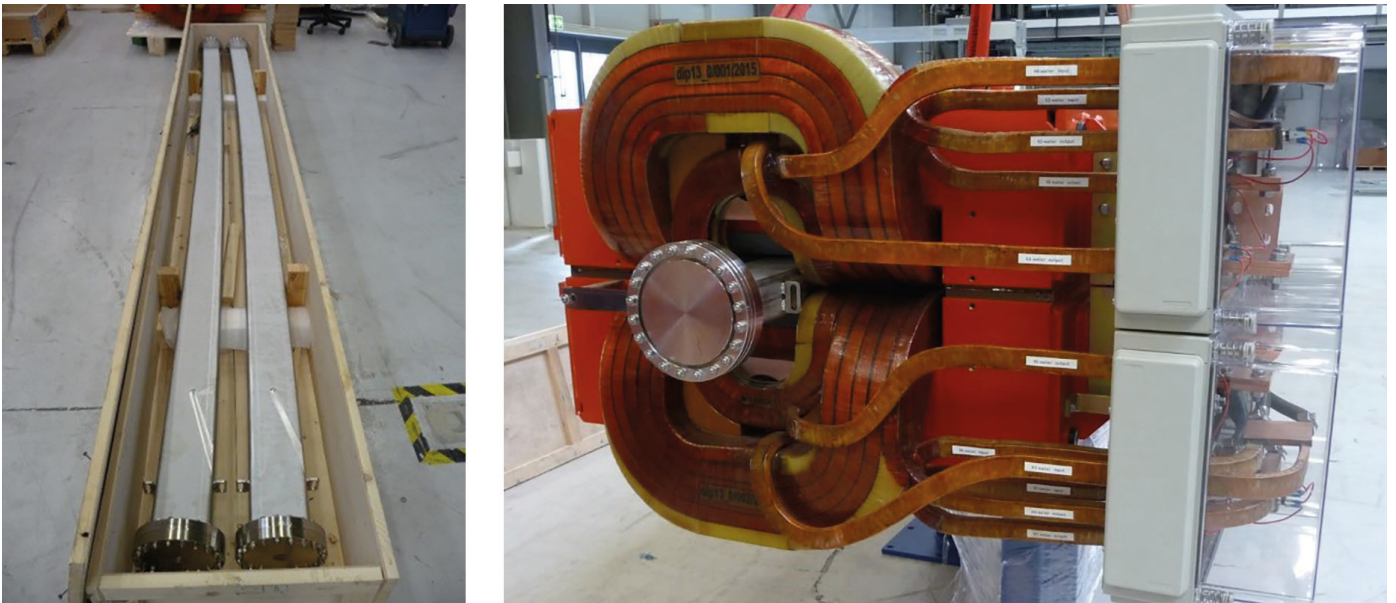


Figure 50. Pre-series vacuum chamber installed into dipole magnet type dip13\_0 at GSI

The vacuum chambers for the dipole magnets of batch1 are built by BINP. After delivery of two pre-series vacuum chambers for dipole magnets of type dip13\_0 to GSI/FAIR and their acceptance in February 2018 (SAT included also the installation of vacuum chamber into the dipole magnet, see Figure 50), 20 series vacuum chambers (14 bent standard vacuum chambers for dipole magnet type dip13\_0, 1 bent vacuum chamber for dipole magnet type dip2\_0, 5 branching vacuum chambers) arrived at GSI on the 16<sup>th</sup> of May 2018, see Figure 51:



Figure 51. 20 series vacuum chambers at GSI

Seven vacuum chambers passed already successfully the SAT, while the SAT of the other 13 vacuum



chambers is currently ongoing. Manufacturing of remaining 29 vacuum chambers of batch1 is completed and the vacuum chambers were already tested at BINP.

## Electric Power - power connection to FAIR/Campus (EP)

### Power Connection to FAIR:

In close cooperation with FAIR S&B, energy provider e-netz and technical department EPS the FAIR transformer stations north and south were put successfully into operation.



Figure 52. FAIR transformer station north

Transformer station north (see Figure 52) started operation at 23<sup>rd</sup> February 2018. That milestone was an important precondition for commissioning of SIS18 and ESR after shutdown 2016-18 and for beamtime 2018.



Figure 53. FAIR transformer station south

Transformer station south (see Figure 53) started operation at 28<sup>th</sup> June 2018. It now supplies the FAIR construction site with electrical energy. These two projects are completely finished!

## Power converters Cables and machine cable management

The task of the work package (2.14.1.10) "Machine cable management" is to give the best cable data quality possible to FAIR S&B and to the planners. All information needed is collected in a comprehensive cable database. It will be used in cooperation with FSB for the cable routing, cable-laying and cable procurement.

## 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 R3B GLAD magnet testing and for the cooling of the CRYRING electron cooler solenoid. The main future customers at FAIR are the SIS100 and the Super-FRS with a total helium inventory of about 8 tons. Additionally, CRY serves small consumers like the final focusing system of APPA and the large scale experiments CBM/HADES and Panda. Furthermore, the department is responsible for the so-called local cryogenics belonging to SIS100 and Super-FRS respectively. In the following different recent activities will be highlighted:



## Cryogenic Infrastructure for the Series Test Facility (STF):



Figure 54. The GSI series test facility

The series test facility (STF) for SIS100 dipole magnet testing was taken into operation in 2015 and since then continuously running for the testing of the first of series (FoS) dipole magnet, for the test of the SIS100 main and local current leads and many other components. Since autumn 2017 serial testing of SIS100 superconducting dipole magnets under cryogenic conditions is the major task of the STF. The STF has an overall cooling capacity of 1.5 kW @ 4 K equivalent and is equipped with four test benches for magnet testing and one universal connection box. All test benches can be operated individually in terms of cool-down, warm-up and 4 K hold. Up to now the plant has about 20,000 h of operation. A picture of the STF cryogenic infrastructure is shown in Figure 54.

## 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 step a 19 kW @ 4 K equivalent cryo plant will be installed, including a campus wide 1.6 km long distribution system. Two industrial studies concerning the cryo plant layout were performed in 2014 and afterwards the specification was continuously adapted to future user requirements. 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 will be ordered in one lot. The procurement phase is currently ongoing:

## The Cryogenic Distribution System:

The cryogenics distribution system is roughly divided into the SIS100 distribution system, the north/south transfer and the Super FRS distribution system. For the SIS100 distribution system an intense study was already undertaken in 2014. Presently the pipe routing is finally adapted with respect to other technical infrastructure installation for the complete distribution system. The tendering is prepared for 2019.

## The Cryogenic Infrastructure for the GLAD Magnet:

For the testing of the GSI GLAD magnet, which will be later, a central component of the high energy branch of the Super-FRS, the cryogenic department has refurbished an existing cryo plant. The refurbishment comprises a complete check of the hardware, the replacement of a large number of actors and sensors, a complete new electronic cabinet and state of the art control software using the CERN

industrial control software environment UNICOS in combination with Siemens WinCC OA. The GLAD magnet was cooled down for the first time in autumn 2017. Presently the GLAD Magnet is cold, filled with liquid Helium and ready for powering.

## Control Systems (ACO)

The accelerator control system for FAIR is continued to be designed and developed as substantial in-kind contribution of the GSI controls group with additional contributions by the Slovenian Tehnodrom consortium.

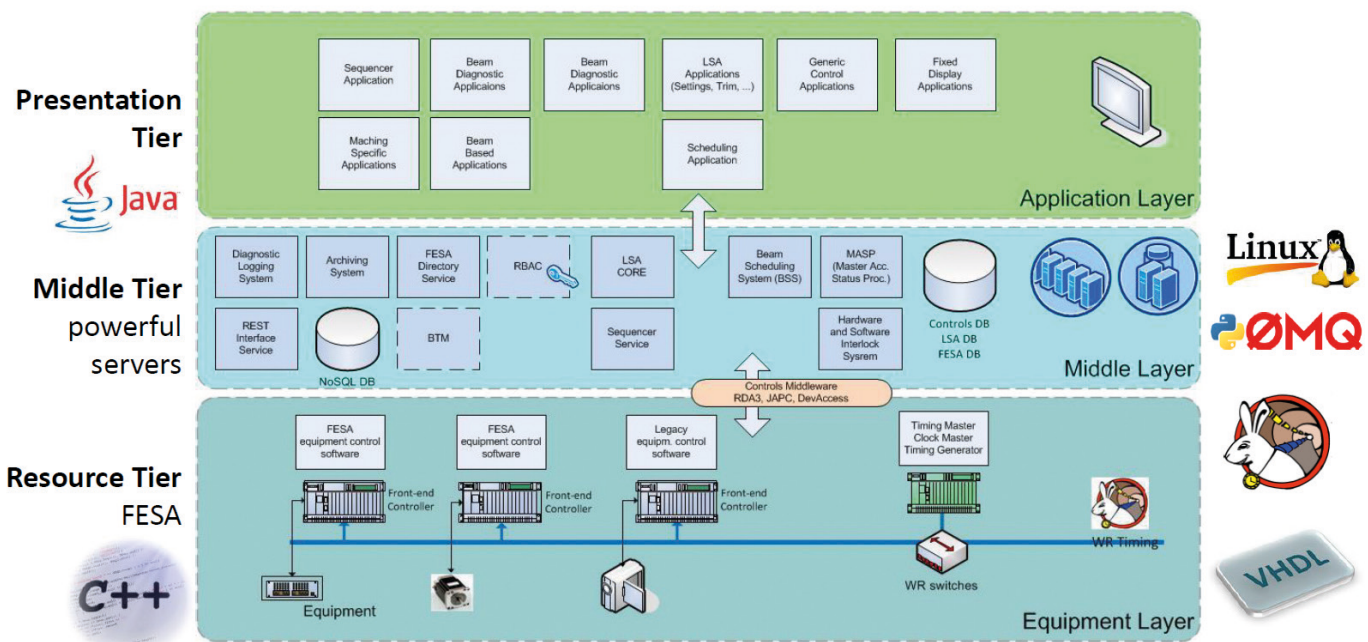


Figure 55. FAIR Control system stack

Consistent with the overall controls development and implementation strategy, full focus of the past months has been put on implementing, testing and commissioning the future FAIR control system at CRYRING and the existing GSI accelerator chain (SIS18, GSI-HEBT, but UNILAC excluded). During the 2-year shutdown period of the GSI facilities, a basic version of the full stack of the new FAIR control system (Figure 55) has been prepared and rolled out to fully replace the technically obsolete existing system. However, far from being feature-complete, first beam with the new FAIR control system in SIS18 was achieved in June 2018 after a sequence of dry-runs and only about two weeks of commissioning. Therefore, the FAIR control system is already in use for FAIR Phase-0 beamtimes, years ahead of the new FAIR machines.

Architecture, basic concepts and general system design have so far shown no fundamental problems or showstoppers. Nevertheless, some technical limits and bottlenecks in individual controls subcomponents have been identified during commissioning and operation, requiring minor 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 the continuing development of FAIR-specific equipment control implementations, the activities of the accelerator controls development team is presently focused to identify and iron out technical issues during operation. Furthermore, dedicated storage ring functionality is under development as required for successful and effective ESR and CRYRING physics operation and as a model of the future FAIR storage rings.





Figure 56. GSI control room refurbished with new FAIR consoles and fixed displays

Moreover, significant progress has been made in the past months on all control system sub-projects:

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, DIO, etc.) have been continued. The first 250 SCU units out of 1200 units have already been produced, of which 100 units are already 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 as a mid-term project for production of the second batch of about 600 units

The full set of stepping motor controllers and multi-serial interface controllers has been delivered as in-kind contribution by the Slovenian project partner and is waiting to be installed in the FAIR facility.

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. Prototypes for both uTCA and PMC have been received, rigorously tested and approved for production.

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 already been started and bids have been received.

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, data-bases, 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.

Development on the accelerator measurement and data archive system has started by the Slovenian in-kind partner; a prototype version is presently being evaluated in the controls lab to confirm the technology choices. Server and storage IT systems are presently under procurement to test the system and perform the SAT approval under real-life conditions during FAIR Phase-0 beamtimes in 2018/19.

On the industrial controls side, vacuum control with the industrial control SCADA-based UNICOS framework has been developed, installed, commissioned and has been successfully tested at the CRYRING

machine. The vacuum bake-out control of all sections of the CRYRING has been already successfully implemented and tested, shortcomings and problems have already be identified and are presently being addressed.

In respect of cryogenic controls, several cryogenic sensors and actuators have been tested as a sound base for the cryogenic controls system design.

Technical and functional specification documents for the control system of the tendering of the FAIR central cryo-plant (Cryo2) have been worked out and are formally approved.

New prototype operator consoles for the future FAIR control center (FCC) have been designed and installed in the present GSI main control room for operation (see Figure 56). A very basic and generic set of completely 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 are already wall-mounted and first accelerator overview applications have been developed.

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, analog signals digitisation system). The implementation of a powerful continuous integration system as well as a deployment and rollout system is still pending due to manpower limitations.

## Transport and Installation (TRI)

Beside supporting the Accelerator Operation Division in service, reconstruction and upgrade of accelerator components during the presently running beamtime program, TRI is strongly involved in the development of strategic logistics concepts for transport, component testing, 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.



Figure 57. External storehouse area ("Halle Weiterstadt")

Review of the need for intermediate storage lead to an extension of the rented external storehouse area in Weiterstadt.

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

Head: Prof. Dr. Mei Bai, GSI

Editorial board: Dr. Giuliano Franchetti, Dr. Winfried Barth, Dr. Wolfgang Geithner, Dr. Lars Groening, Dr. Petra Schütt, all GSI

During the 2nd half of 2018, Accelerator Operations Business Area continued to focus on the realization of FAIR Phase-0 as well as updating and upgrading of existing accelerator facilities in particular UNILAC, and critical infrastructures such as Galvanic workshop.

After recovered from the ER1 power converter arc incident due to the unexpected defect of the LINAC RF gallery air cooling system, the Accelerator Operations business area (ACC) has successfully carried out its first engineering run in the winter of 2018 and Physics Run in the first quarter of 2019. Besides limitations on re-establishing the expected operation capabilities such as high intensity heavy ion beams, parallel operations, beam stacking in storage rings due to major technical issues such as the high intensity RFQ (HSI RFQ) as well as the commissioning of the FAIR accelerator controls, all goals of the Engineering Run and Physics Run were achieved. For more details see Section 13.1.

In parallel to the execution of beam time, dedicated efforts have been organized and carried out to address the major technical limitations in the UNILAC area, i.e. reproduce the HSI RFQ electrodes and carrier rings, produce a new beam pipe for the LEBT QQ to allow operation mode that requires changes of beam patterns above average 1 Hz repetition rate, as well as the planned UNILAC UHV upgrade. The damaged ER1 power converter of UNILAC single gap resonators that are required for fine energy adjustment for UNILAC experiments such as Super Heavy Elements SHE, is also cleaned and in good progress of repair. Meanwhile, a thorough investigation of the technical capability of current GSI accelerator facilities was carried out.

At the same time, ACC continues its commitments to the FAIR project in leading the work packages of p-Linac proton source, p-Linac RF, dedicated uranium injector as well as the Stochastic Cooling for the Collector Ring (CR). For more details see Section 13.3. The operation infrastructure support of ACC, i.e. the Galvanic workshop and the mechanic workshop as well as the technology laboratory, continues its strong technical support to the whole campus (see Section 13.4).

In addition to its collaboration with the accelerator technical groups in the project division, ACC also intensifies its engagement in many other areas and divisions to ensure its activities and planning are transparent to campus and in coherence with the overall GSI/FAIR strategic goals. It is now in regular discussion with the project management office regarding resource balancing, and with campus development team to further improve communication and coordination of campus development activities with tight interfaces to the GSI accelerator complex.

The scheduled 2019 shutdown work started right after the beam time. It will continue until the beginning of next engineering run planned for end of 2019. All activities were prioritised based on their importance with respect to the beamtime, FAIR commissioning, as well as FAIR operation. These activities are scheduled and coordinated based on the priority as well as on available resources.

As usual, the Accelerator Operations continues its engagement with neighbour universities for training next generation of talented work force, and continues to provide the communication platform for the accelerator experts by hosting the Accelerator Seminar, as well as the Operations Physics and Technology salon to promote the open academic exchanges among colleagues. This platform is also designed for young and talented students and junior staff members to be closely engaged and inspired.



## 13.1 Engineering run and shut-down prolongation (Operation and beamtime performance)

Author: Stephan Reimann, GSI

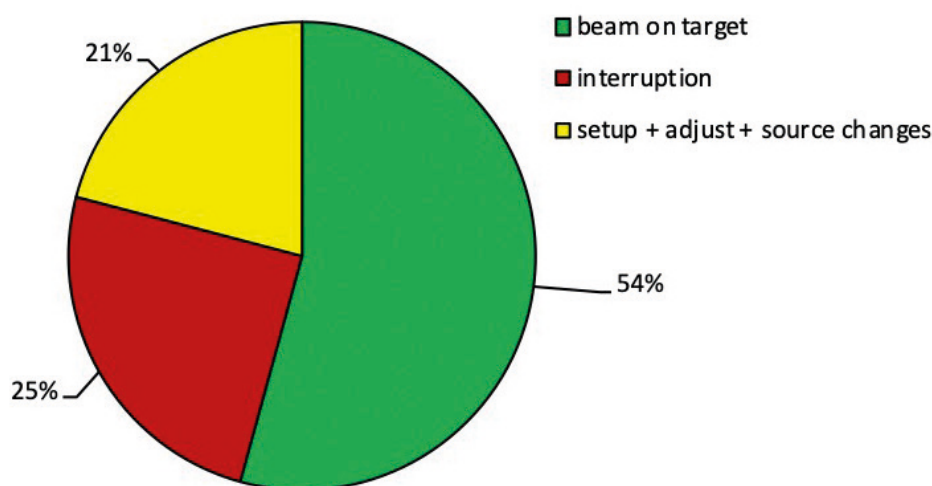


Figure 58. Overall statistics for beam time period from June 12th to July 13th, 2018.

After a two years shutdown period with numerous upgrade- and maintenance works, the whole GSI accelerator chain should be re-commissioned to provide a physics run starting June 12th. Despite the delays connected to the HVAC renovation and the GAF project, the accelerators could be restarted right on time. After a lot of efforts, that were put into 8 dry runs, and an intense commissioning phase, the UNILAC was back in operation to serve the users as scheduled from June 12th. While the performance was sufficient for most of the scheduled UNILAC users, it turned out that we could not reach more than 60% of the HSI-RFQ design power after more than three weeks of conditioning. This significantly limited the UNILAC capability in providing the expected performance for the heavy ion beams (e.g. silver, lead or uranium) that were requested by the experiments at SIS-18 area such as HADES or FRS. A lot of effort has been made to mitigate the impact by using alternative ion species as well as developing higher charge states from the ion source to overcome the limits of the RFQ. In the end, new electrodes had to be ordered.

In parallel, the commissioning of the SIS18 and the high energy transfer lines with the new FAIR controls started accordingly. The initial setup with beam in SIS18 went very smoothly, and pilot beams were brought to four target stations such as HHD, HTP, HAD and HTA. Nevertheless, the full-scale beam setup and optimization to all target stations with the new controls remained to be a big challenge to the operations team as most of the software was still in a preliminary state.

The planned campaign mid of July to develop the performance and conditions that were requested by HADES and FRS was interrupted unexpectedly by an arc of the ER1, a power amplifier for an UNILAC single gap resonator. This incident also prohibited the intended comparison of the performance of two titanium ion sources. The scale of the damage significantly undermined the condition of safe operation, and therefore operation was suspended until the safe operation condition could be re-established.

After the unscheduled shutdown due to the arc incident at ER1 power converter in the LINAC RF gallery and the necessary cleaning and repair measures, the re-commissioning of the GSI accelerator facility



was resumed at the end of 2018. In order to assure a smooth operation in 2019, an engineering run was carried out at the beginning of Nov. 2018. The goal was to establish, evaluate, and improve all beam setups for the scheduled experiments, while the experimental campaigns planned in summer 2018 were postponed to the beginning of 2019. Special attention was paid to the challenging beam setup for experiments such as HADES.

At the beginning of the engineering run, the UNILAC-RF systems were recommissioned and conditioned. With the exception of the single gap resonator (ER1), all systems were ready for operation in November 2018. Since the ER1 was not required for the experiments scheduled for the beam time 2019, the final repair was postponed to 2019. Further limitations resulted from the voltage limitation of the HSI-RFQ to 60% of nominal value. In addition, parallel operation was still limited: at UNILAC due to the LEBT QQ (Low Energy Beam Transport quadrupole quartet), and at SIS18 and HEST (Hochenergiestrahl-führung) full performance of the new FAIR accelerator control system could not be achieved.

During the engineering run, the accelerator chain for all planned target stations was tested with beam. Since the new FAIR control system was operational for all accelerators except UNILAC, the main focus was laid on the SIS18 and the high-energy beam transfer lines. The required parameters and beam properties (intensity, focusing and spill structure) were reproduced and verified, and the possibilities for further improvement were also identified. For the first time, the extraction time could be increased to more than 20s and, with a novel micro-spill correction, the usable event rates for experiments with slow extraction were improved significantly.

During the engineering run, both electron coolers (SIS18 and ESR) were operational and their functioning was re-established with beam. Although all required functionalities of the FAIR control system for the ESR could not be fully implemented, yet, the ESR team successfully managed to inject the SIS18 beam into the ESR and subsequently store and cool the beam.

After a short-scheduled shutdown, the user beam time began as scheduled on 2019-02-21. Conservative beam time planning to ensure the scheduled Physics programs enabled high efficiency and availability of the entire accelerator facility right from the start. The main experiment HADES was able to achieve the desired number of events already before the end of the planned beam time. With a new hysteresis correction at SIS18, parallel modes could be re-established in some cases. Thus, beam was provided for the ESR commissioning and various operating modes (storage, cooling, deceleration) could be tested.

|       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SIS18 | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 100-300MeV/u, fast + slow + k.o., 2.0E8 particles per spill extracted (reduced!, 1.0E9 optional)</li> <li><math>^{107}\text{Ag}^{42+}</math>, 300MeV/u, fast, slow, fast + cooled</li> <li>3.0E7 particles per spill (sustainable), up to 1.0E8 possible after high-transmission optimization of UNILAC</li> <li><math>^{107}\text{Ag}^{45+}</math>, 1580MeV/u, slow</li> <li>1.0E7 particles per spill (sustainable)</li> </ul> |
| ESR   | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 262MeV/u, fast, cooled</li> <li><math>^{107}\text{Ag}^{45+}</math>, 232MeV/u, fast, cooled</li> </ul>                                                                                                                                                                                                                                                                                                                            |
| HADES | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 300MeV/u, slow,</li> <li><math>^{107}\text{Ag}^{45+}</math>, 1580MeV/u (18.48Tm), slow 14s</li> </ul>                                                                                                                                                                                                                                                                                                                            |
| HTC   | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 500MeV/u, slow</li> <li><math>^{107}\text{Ag}^{45+}</math>, 600MeV/u, slow</li> </ul>                                                                                                                                                                                                                                                                                                                                            |
| HTD   | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 500MeV/u, slow</li> <li><math>^{107}\text{Ag}^{42+}</math>, 950MeV/u, slow</li> <li><math>^{107}\text{Ag}^{45+}</math>, 1200MeV/u, slow</li> </ul>                                                                                                                                                                                                                                                                               |
| HTM   | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 300MeV/u, slow</li> <li><math>^{40}\text{Ar}^{18+}</math>, 300MeV/u, k.o.</li> </ul>                                                                                                                                                                                                                                                                                                                                             |
| HTA   | <ul style="list-style-type: none"> <li><math>^{40}\text{Ar}^{18+}</math>, 300MeV/u, slow</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                        |

Figure 59. List of established beams during engineering run in 2018.

With great effort at the beginning of the engineering run, the control system could be stabilized to such an extent that smooth operation of all accelerators could be guaranteed. The CRYRING was also operated in parallel with its local injector. Despite various problems with the helium supply of its electron cooler

during its beam time, the CRYRING was able to have rather stable operation for several weeks without major technical interruptions.

In summary, the operation of the GSI accelerator facilities for intermediate scientific research towards FAIR is successfully re-established. Major technical restrictions that limited its scope of user operation have been addressed and are planned to be overcome by the end of 2019.

Here is the list of highlights achieved during the reporting period:

- Steady operation with beam-on-target reached ~80% of the accelerator uptime. All requested ions for the physics program were delivered. Parallel operation in block mode was carried out.
- Significant improvement in micro-spill structure quality of the slow extracted beam from SIS18. This directly resulted in a net increase of 45% of data recorded.
- ESR commissioning in the synchrotron mode of the control system continued, and beam was successfully decelerated to 110 MeV/u. Further deceleration requires successful realization of ESR storage ring mode in the FAIR accelerator control system, a task that is foreseen for later 2019.
- The new FAIR control system was used in a production beam time for the first time at all accelerator except the UNILAC. The operation was very stable and in special cases even parallel operation modes have been applied.

## 13.2 Accelerator research & developments

### 13.2.1 CW-Linac R&D

Author: Wolfgang Barth, GSI

Two additional demonstrator machine runs have been accomplished in 2018 after successful commissioning of the demonstrator cryomodule equipped with a 217MHz multi gap Crossbar H-mode structure (CH) and first testing with beam from the GSI High Charge State Injector (HLI). The required acceleration gain of 0.5MeV/u has been confirmed with heavy ion beams at maximum available beam intensity and full beam transmission. Further systematic heavy ion beam measurements with varying RF-amplitudes and -phases of the CH-cavity were accomplished. The worldwide first and successful beam test campaign with a superconducting multi gap CH-cavity is a milestone of the R&D work in preparation of the entire superconducting (sc) continuous wave (cw) heavy ion Linac project and other cw-ion beam application. Meanwhile further experiences have been gained in design, fabrication and operation of superconducting CH-cavities and the associated components. Newly developed beam instrumentation, as a cold beam position monitor, an advanced beam transformer for cw-application (DCCT) and a bunch structure monitor (Feshenko monitor) have been developed, built and tested with heavy ion beam.

The cw-Linac layout meanwhile underwent a complete revision. Optimized cavity layouts resulted in modified voltage distributions. Furthermore, the layout - now with three CH-cavities and a rebuncher per cryomodule - has been specified with more details. It features high acceleration efficiency with longitudinal and transversal stability, as well as a straightforward energy variation. Highly charged ions will be accelerated from 1.4MeV/u up to 3.5- 7.3MeV/u. The newly developed design is sufficient to accelerate light up to heavy ions (1A/q8.5). It is already confirmed experimentally that CH-cavities with equidistant rf-structure potentially could accelerate ions up to beam energies even beyond the design limit.

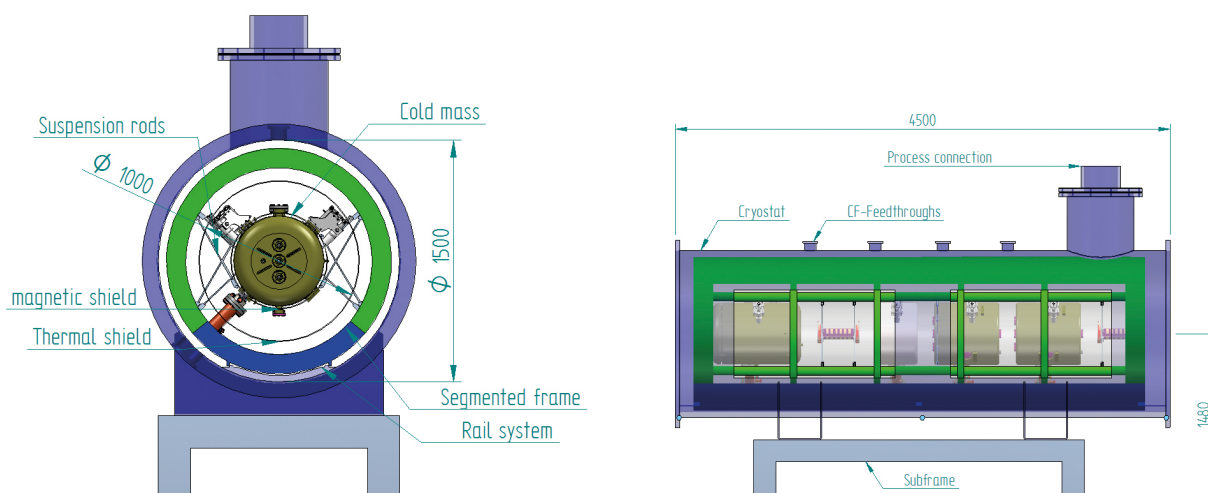


Figure 60. Advanced cryomodule layout, with four rectangular service doors and Nuclotron suspension of single components; the segmented support frame is mechanically and thermally coupled to outer tank (300 K), the thermal shield is mounted inside the support frame. The transverse position of each component will be preserved within  $\pm 0.1$  mm during cool down (courtesy: CRYOWORLD Co.).

An advanced cryomodule, comprising demonstrator cavity and two new short CH-cavities, a sc-rebuncher cavity and two superconducting solenoids is already in preparation: The first short cavity with a revised design, has been successfully tested at a vertical test cryostat confirming impressively the high gradient capabilities of sc CH-cavities. The second cavity was recently delivered as well - rf-testing will start soon. The sc-rebuncher design is almost carried out, purchasing of niobium will start soon. The newly designed 5m long cryostat could be ordered in February 2019, specifications for solenoids, rf-couplers, vacuum systems and rf-amplifiers are fixed, the purchasing process is still ongoing. A newly developed bunch structure monitor is still in the manufacturing process.

At GSI (Darmstadt) the test demonstrator area extension for housing the advanced cryomodule has been already started. A new area for setting up the rf-amplifiers, control racks, an rf-test lab and for storage capabilities will be finished until mid of 2019. Two 4.5t (22.5degree) dipole magnets (recently transferred from CERN to GSI) are renewed for insertion at the cw-linac transport line. The link to the GSI cryo infrastructure could be successfully installed in January 2019, supplying the test area as well as the cw-Linac, the accompanying LHe-transfer has been already ordered. The new infrastructure for SRF R&D has been set up at the HIM. Besides a radiation shielded test area, the main feature is a 155m<sup>2</sup> clean room facility with its key components: An Ultrasonic bath and a conductance rinse, a high-pressure rinsing device and a 120°C vacuum oven. The equipment is now set up and well suited for the installation and testing of a CH-cavity in 2019.

## Publications of 2018

- Yaramyshev, S. ; Aulenbacher, K. ; Barth, W. ; et al.: **Advanced Approach for BeamMatching along the Multi-Cavity SC CW Linac at GSI.** *Journal of physics / Conference Series Conference Series 1067, 052005* (2018), DOI:10.1088/1742-6596/1067/5/052005
- Schwarz, M. ; Aulenbacher, K. ; Barth, W. ; et al.: **Beam Dynamics Simulations for the New Superconducting CW Heavy Ion LINAC at GSI.** *Journal of physics / Conference Series Conference Series 1067, 052006* (2018), DOI:10.1088/1742-6596/1067/5/052006
- Barth, W. ; Aulenbacher, K. ; Basten, M. ; et al.: **First heavy ion beam tests with a superconducting multigap CH cavity.** *Physical review accelerators and beams 21(2), 020102* (2018), DOI:10.1103/PhysRevAccelBeams.21.020102
- Taletskiy, K. ; Gusarova, M. ; Barth, W. ; et al.: **Comparative Study of Low Beta Multi-Gap Superconducting Bunchers.** *Journal of physics / Conference Series Conference Series 1067, 082006* (2018), DOI:10.1088/1742-6596/1067/8/082006
- Gusarova, M. ; Kiselev, D. ; Miski-Oglu, M. ; et al.: **Multipactor discharge in superconducting accelerating CH cavities.** *Journal of physics / Conference Series Conference Series 1067, 082007* (2018), DOI:10.1088/1742-6596/1067/8/082007

## 13.2.2 Testing and commissioning of ESR

Author: Markus Steck, GSI

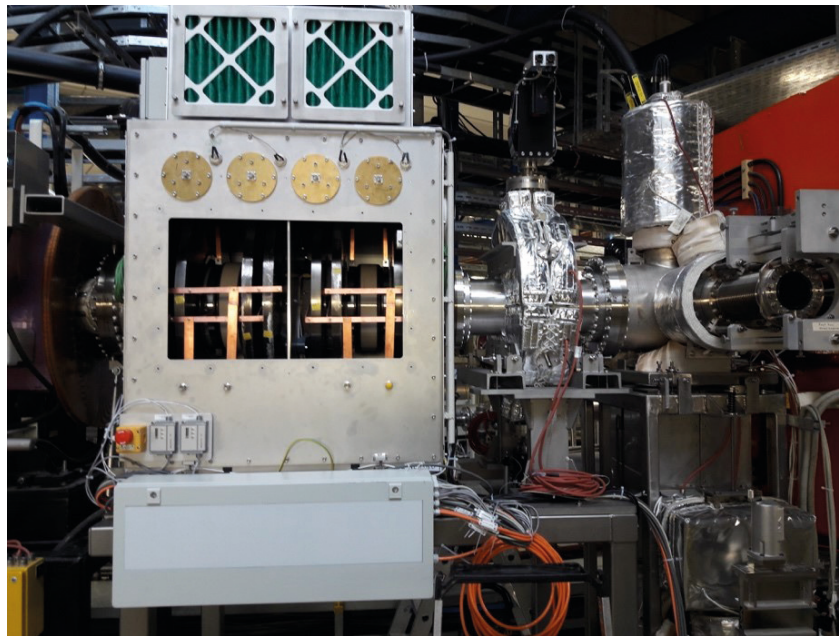


Figure 61. The new barrier bucket cavity and the second Schottky resonator after installation in the Northern arc of the ESR.

In the first part of 2018 various maintenance and repair activities were performed in order to prepare the ESR for the re-commissioning with the new control system. When the northern arc was opened for the repair of a leaking dipole vacuum chamber, as well new ring components namely a broad-band barrier bucket rf system (pulse frequency up to 5 MHz) and a second resonator-type Schottky pick-up were installed at the original location of the second harmonic ferrite cavity.

Moreover, new control and digitization units for beam diagnostics were installed and tested. The upgraded control system was prepared for operating the ring in the synchrotron mode. A mode which allows beam storage for periods of arbitrary length and manipulation of ring components, while the beam is stored, was not available in 2018, but is prepared for the coming year. Most of interfaces between control system and power converters (about 100 units) were modernized. The new control system was commissioned in various test periods without beam operation. After completion of the shutdown activities, in the course of October proper control of all components of the ring and of the electron cooler as ramped devices was achieved in the synchrotron mode. Although the electron cooler devices were ready for ramped operation, electron beam was produced during the coming commissioning time mainly in a static mode in order to minimize the risk of damage due to faulty operation. During December the re-commissioning with beam from SIS could be performed during a few days. Coupling of the ESR cycle to the SIS cycle and synchronization of the kickers was achieved. Data sets stored in the old control system could be readily used for beam transport from SIS to ESR with the new control system. Although the available time with beam was rather limited, various aspects of ESR operation could be tested. Stable storage of  $^{107}\text{Ag}^{45+}$  at 232 MeV/u for a period of 15 seconds, which was limited by the operation in the synchrotron mode, was demonstrated. The beam could be cooled by electron cooling demonstrating the operational availability of the system. First measurements of the beam orbit after injection with the new beam position monitor system were successful. The standard Schottky diagnostics were available for commissioning, in addition first signals could be observed with the newly installed resonator tuned to a frequency around 407 MHz. Further progress in the ESR re-commissioning and optimization of the ring parameters will strongly depend on the availability of the storage ring mode which is planned for implementation in 2019.



### 13.2.3 CRYRING commissioning 2018

Authors: Zoran Andelkovic, Frank Herfurth, all GSI

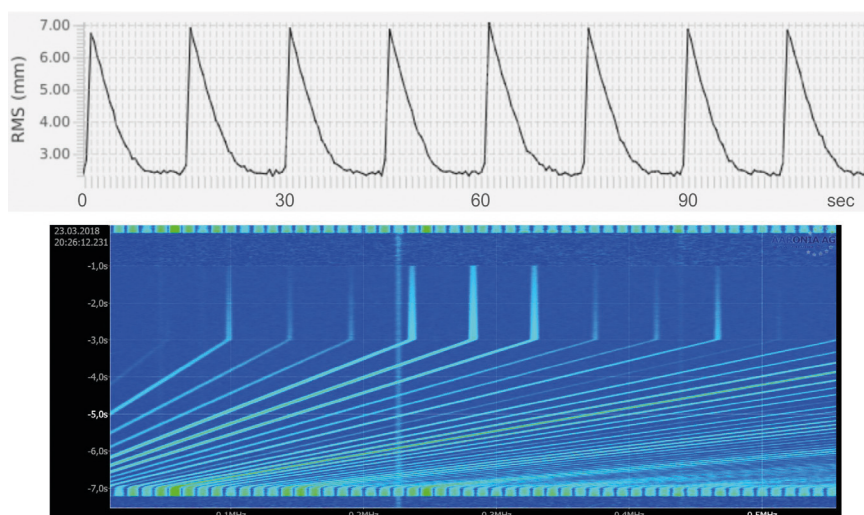


Figure 62. Upper part: eight cycles of D<sup>+</sup> in CRYRING observed on the ion position monitor. The reduction of the beam width due to electron cooling can be clearly seen. Lower part: Schottky spectrum of Mg<sup>+</sup> at CRYRING recorded over several harmonics during acceleration to 32 keV/nucleon.

In 2018 four commissioning runs were scheduled with an average duration of three weeks. The first run in March was used to accelerate H<sub>2</sub><sup>+</sup> ions to the maximum rigidity of the ring (24 MeV/nucleon), as well as to store Mg<sup>+</sup> for the first time. The ions were produced by a Nielsen-type ion source (MINIS) at 1-3 keV/nucleon (Ar<sup>+</sup>, Mg<sup>+</sup>) as well as at 300 keV/nucleon (D<sup>+</sup>, H<sub>2</sub><sup>+</sup>) in combination with a radio frequency quadrupole structure. A typical ion current of 2-20 μA, depending on the ion species, was stable at the injection for around one to two weeks, followed by a regular maintenance of the source. A beam lifetime of 5 seconds and 15 seconds was observed for H<sub>2</sub><sup>+</sup> and Mg<sup>+</sup>, respectively, attributed to the collisions with the residual gas particles. The measured integral value of the ring vacuum amounted to around 8·10<sup>-11</sup> mbar, a value slightly better than in 2017, mostly due to repair of minor leaks, longer pumping periods and additional baking of the beamline.

Further two beamtime periods were cancelled and commissioning with beam was put on standby until autumn because of simultaneous commissioning of other GSI accelerators and lack of manpower in various expert groups at GSI. Thus, the final commissioning with beam of the year took place in October. The ion of choice was singly charged deuterium, because of the favourable mass for the acceleration in the RFQ as well as because of large beam lifetime in the ring. Around 10<sup>8</sup> particles were stored in the ring with an exponential decay constant of around a minute.

After extensive repairs in the summer, the electron cooler was operational for the final commissioning run. The superconducting magnet was filled with liquid helium and energized to 2.6 T, resulting in an electron beam expansion factor of 65. Including one refilling period, the magnet remained superconducting for around 10 days. That was sufficient to demonstrate electron cooling of the deuterium beam stored at the injection energy of 291 keV/nucleon. Full commissioning of the electron cooler with up-graded controls and ramped operation is planned for 2019.

The installation of the first experimental setups at CRYRING was started between the commissioning periods. A laser spectroscopy setup included a vacuum chamber with an elliptical mirror and three optical windows. Transparent for ions beams, the chamber reflects the fluorescence from an ion beam towards PMT detectors. A laser beamline was installed between the CRYRING laser laboratory and the ring. Two beam scraper systems were installed in the same section of the ring to facilitate the overlap of

the ion and laser beam. First experiments with laser spectroscopy and fluorescence are expected in the following year. A prototype setup for measuring dielectronic recombination was prepared for testing with ion beam: experiment controls were synchronized to and triggered by the ring cycle; the relative energy scanning of electron-ion collisions is controlled through the electron gun potential from the experiment; for measuring electron-ion recombination products the first detector setup (for primary ion charge states  $q < 20+$ ) was successfully tested at 300 keV/u and higher, and the second system ( $q > 30+$ ) is ready for testing and waiting for a ions of suitable initial charge state.

### 13.2.4 Cooling Progress and Status of the three GSI electron coolers in 2018

Authors: Regina Heß, Michael Bräscher, Christina Dimopoulou, Michael Peter Kelnhofer, Jürgen Krieg, Holger Liebermann, David Ondreka, Jon Roßbach, all GSI

In 2018 the electron coolers of SIS18, ESR and CRYRING were maintained and recommissioned for proper operation with the new control system. Focusing on the engineering runs of the SIS18 and the ESR, the main efforts concentrated on retrofitting to the new control system. For all three electron coolers, a physics data supply model was set up and implemented into the new control system down to the device (e.g. power supply for cooler magnet or high voltage) level. Following the new hierarchy, proper calculation and transmission of the main parameters to about 100 cooler devices (including ion orbit correctors adjacent to the cooler) was verified thoroughly prior to the beam-times.

#### SIS18

During standalone runs in summer 2018, the functionality of the cooler could be shown. A data supply pattern was created for the cooler within the SIS18 cycle (synchrotron mode), as in the former times. Finally, in December 2018, the full functionality and adjustability of the electron cooler (including ramps for the magnets) could be demonstrated with SIS18 beams at injection energy. It was possible to switch on/off the electron beam by means of timing events, and adjust the acceleration voltage, the electron current and the magnetic field. In addition, the new data supply model allows expert operation of the cooler e.g. as an electron lens.

ESR:

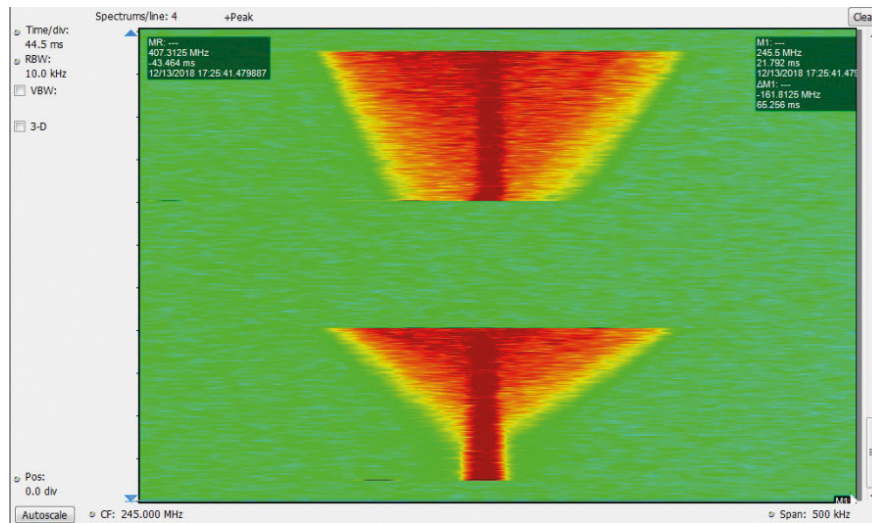


Figure 63. Reduction of the momentum spread of a stored ESR  $^{107}\text{Ag}^{45+}$  beam at 232 MeV/u – acceleration voltage 127.42 kV, Electron current upper:  $I_{\text{el}}$  125mA; lower  $I_{\text{el}}$  250 mA.

During the long shutdown, the ESR electron cooler had been vented for inspection and refurbishment. Subsequently it was baked and the new cathode as well as the “high-voltage” were conditioned. Stand-alone recommissioning of the device by successful guidance of an electron beam from the gun to the collector was achieved. In December 2018, the successful cooling of a stored ion beam in the ESR was demonstrated. The operation of the cooler devices was carried out in DC-mode.

CRYRING:

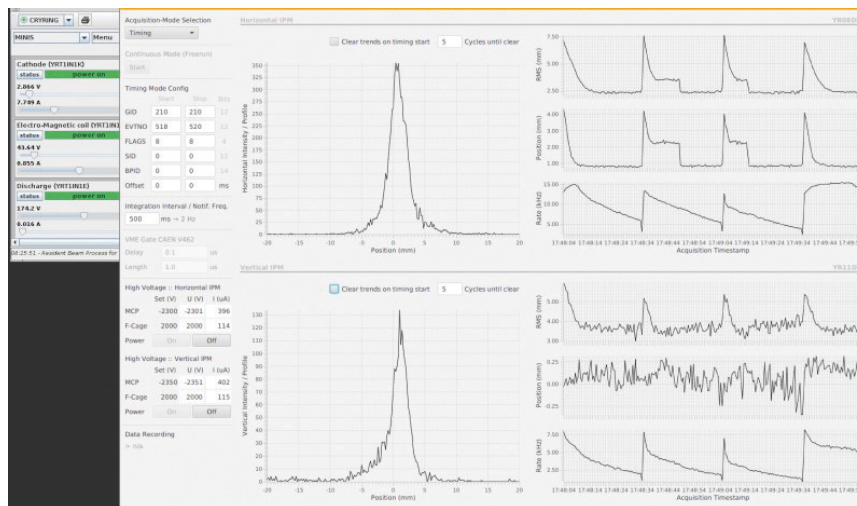


Figure 64. Horizontal and vertical profile (left) and RMS size (right) of the 291 keV/u  $\text{D}^+$  beam during cooling, measured with the ionization profile monitors.

During two weeks' run in November 2018, the electron cooler was used for cooling of a  $\text{D}^+$  beam at an injection energy of 291 keV/u: Optimum settings were: actual acceleration voltage of 161.2 V (measured with the HV divider), electron beam current of 0.4 mA.

With the data supply model only one setting of the cooler per cycle was possible (pulsed mode). Hence

the ion beam could be cooled either at injection energy or after acceleration (for example at 809 keV/u). The ramped mode which allows to vary the cooler parameters in accordance to the ring acceleration cycle was not yet available.

In summary, all three electron coolers were back in operation mid-December 2018. Necessary measures are underway to ensure a ramped operation mode for ESR and CRYRING coolers during the engineering runs in 2019.

## 13.3 General R&D for accelerators

### 13.3.1 Cathode development for high current ion sources

Authors: Aleksey Adonin, Ralph Hollinger, all GSI

#### Introduction

Development of high current vacuum arc ion sources (VARIS) at GSI were concentrated mostly on heavy elements in the last year: Bi and Pb. The goal was to establish a "standard" operation with 1 Hz keeping stable performance and high production efficiency of  $4^+$  ions. Besides, it is of a great importance to establish a production routine for cathodes with a good reproducibility of the cathode quality. Additionally, due to the recent problems with the HSI RFQ, it was important to test the production efficiency and the operation performance of the VARIS ion source for  $5^+$  ions.

#### Bi cathodes

For production of high current  $\text{Bi}^{4+}$  ion beams a special Bi-Cu (40% Wt.) composite material is used in the cathodes [1,2]. Not only the material composition is important, but also the material structure plays a significant role. Previous tests at Terminal North in Sep. 2017 have shown that the best operation performance was achieved using cathodes with a special material structure, namely Cu "litz wire" homogeneously filled with Bi [3]. The manufacturing procedure of such cathodes is rather complicated and it is difficult to achieve a good reproducibility of the cathode quality.

In August and September 2018, the tests of various production sets of Bi-cathodes have been performed at Terminal North. High performance of "litz wire" cathodes was confirmed: after a short conditioning time (about 20 min) a beam current of 10 mA of  $\text{Bi}^{4+}$  ions has been achieved in front of the RFQ (UH1-section). Stable operation with pulse-to-pulse intensity fluctuations below 15% was demonstrated, that is extremely good for ion sources of vacuum arc type. The lifetime of one single probe was more than 24 hours with 1 Hz repetition rate.

Another important result was successful production of  $\text{Bi}^{5+}$  ion beams. The operation performance of the ion source for  $\text{Bi}^{5+}$  is notably degraded: noisy beam pulse, high pulse-to-pulse intensity fluctuations, and low production efficiency at the beginning that result in a beam current of 2-3 emA in UH1. However, with time (with cathode burning) the situation is improving and after about 10 hours of operation with 1 Hz it was possible to achieve 5 emA of  $\text{Bi}^{5+}$  in front of the RFQ with improved stability.



## Pb cathodes

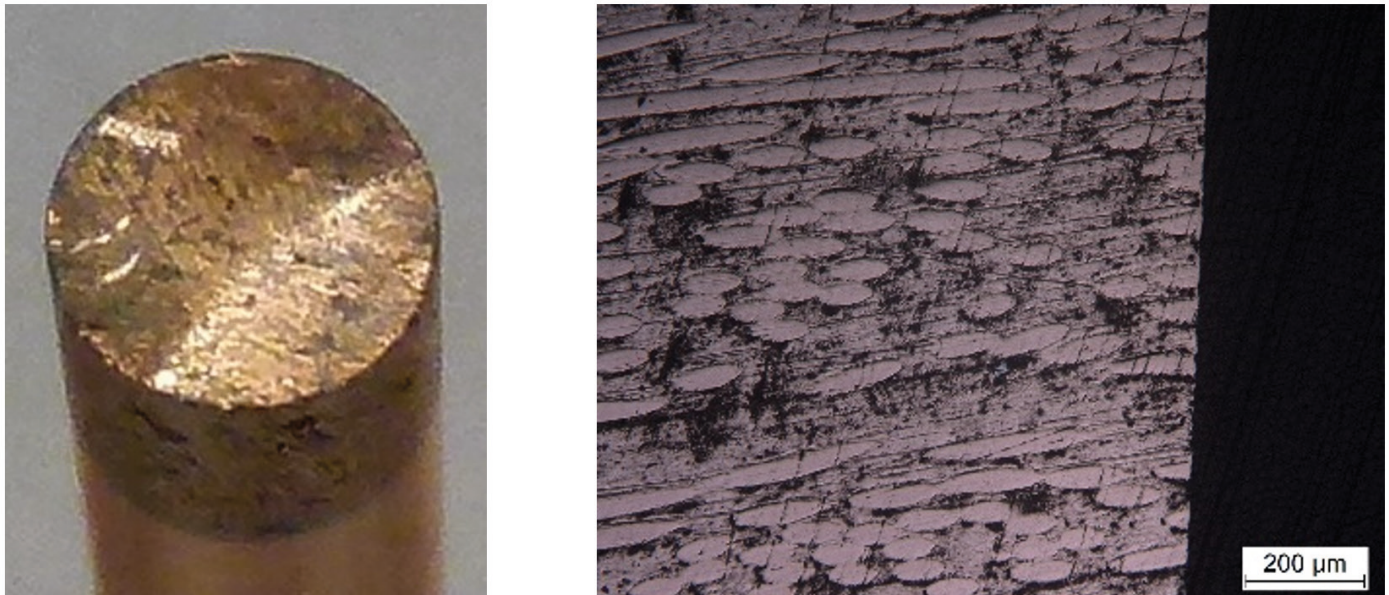


Figure 65. "Litz wire" Pb-Cu (40% Wt.) composite cathode (left); material structure on longitudinal cut of the cathode under optical microscope (right).

After successful tests of "litz wire" the Cu-structure in Bi-Cu composite cathodes in 2017 [3], the same production process was implemented for Pb-Cu (40% Wt.) cathodes. In March 2018 the first set of five experimental cathodes with natural lead has been manufactured by Fa. Hauner and tested at GSI. Figure 65 shows the structure of the "litz wire" Pb-Cu cathode.

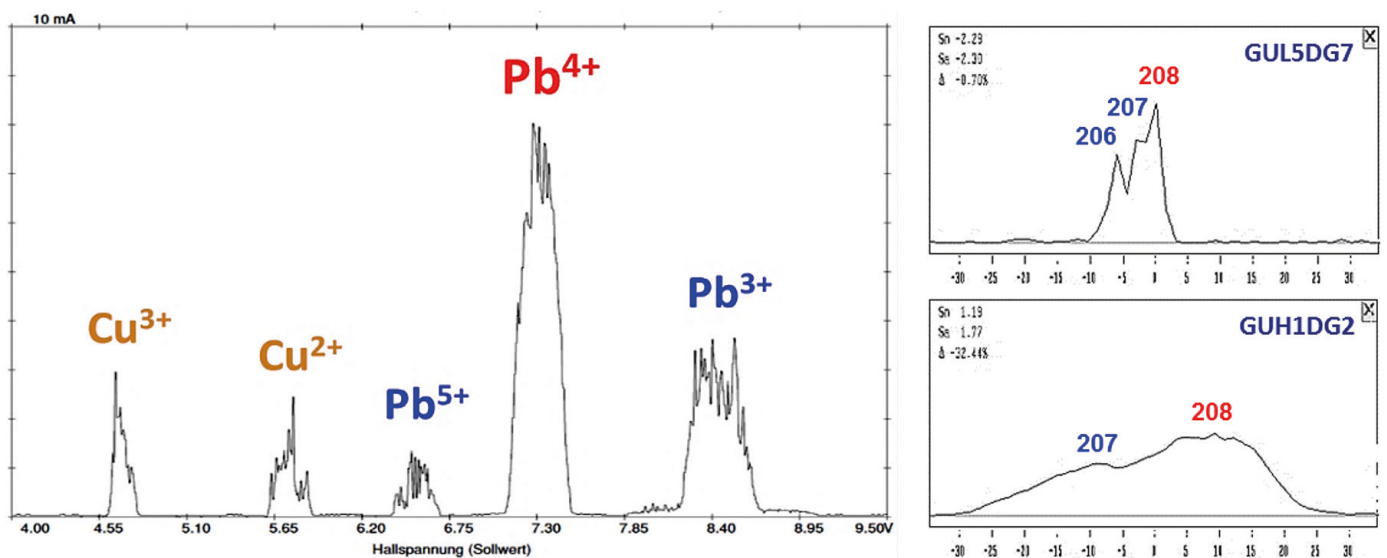


Figure 66. Mass-spectrum of lead measured in LEBT (left); separation of lead isotopes in LEBT demonstrated with profile grids (right).

In the tests all experimental cathodes have demonstrated notably better operation performance compared to previously used material structures and production methods: SM (fused metal), PM (pressed metal powder), infiltration. It was possible to get 5 emA of  $\text{Pb}^{4+}$  already after 20 minutes of conditioning. A maximum ion beam current of 7 mA in front of the RFQ could be reached after some hours of operation. Improved pulse-to-pulse stability with intensity fluctuations below 15% was achieved for 1 Hz operation. High production efficiency of about 50% for  $\text{Pb}^{4+}$  ions one could see from a mass-spectrum (Figure 66). Also, the new cathodes have demonstrated a long lifetime of more than 24 hours with 1 Hz operation.

Another important aspect of the tests was the separation of Pb-isotopes in the LEBT. Since lead has three main isotopes with masses, which are very close to each other:  $^{206}\text{Pb}$  (24%),  $^{207}\text{Pb}$  (22%) and  $^{208}\text{Pb}$  (52%), therefore, it is non-trivial task to separate them. It was shown that for high current Pb-beams from VARIS ion source it is not possible to get a clear separation of the isotopes in the existing LEBT. However, using a special focusing scheme (with focal spots in front of the dipole magnet and behind it) and the slits, it is possible to separate  $^{208}\text{Pb}$  ions with a small admixing of  $^{207}\text{Pb}$ . Figure 66 shows the signals from profile grids behind the first dipole magnet (UL5 section) as well as behind the switching magnet (UH1 section).

As a disadvantage of this option, the intensity of the desired ion beam ( $^{208}\text{Pb}^{4+}$ ) is drastically reduced: only 0.8 emA could be achieved in front of the RFQ. Due to this reason the cathodes with enriched material ( $^{206}\text{Pb}$  and  $^{208}\text{Pb}$ ) have been manufactured. In May 2018 the enriched Pb-cathodes of both types have been conditioned, tested and prepared for the beamtime.

## Conclusion

The "standard" operation with 1 Hz repetition rate has been successfully established for both heavy elements: Bi and Pb for  $4^+$  ions thanks to the new "litz wire" material structure of composite cathodes. Stable operation with up to 5 emA of beam current in front of the RFQ was achieved for  $\text{Bi}^{5+}$  ion beam. As the next step, an improvement of the manufacturing process in order to increase the reproducibility of cathodes quality is foreseen. Also, it is planned to test the new material structure for Au-Cr composite cathodes to improve the ion source performance for  $\text{Au}^{4+}$  ions.

## Publications

- [1] Adonin, A. ; Hollinger, R.: **Development of high current Bi and Au beams for the synchrotron operation at the GSI accelerator facility**. *Review of scientific instruments* 83(2), 02A505 (2012), DOI:10.1063/1.3670743
- [2] Adonin, A. ; Hollinger, R.: **Challenges of production of high current four-fold Bi and Au beams from vacuum arc ion sources at GSI accelerator facility**. In: *25th International Symposium on Discharges and Electrical Insulation in Vacuum, ISDEIV 2012, Tomsk, Russia, 2 Sep 2012 - 7 Sep 2012 s.l. : IEEE* (2012)
- [3] Adonin, A. and Hollinger, R.: **New results on development of 2.7 Hz operation for heavy elements from high current ion sources**, In: *GSI Scientific Report 2017, GSI Report 2018-1, 340-341 p.*, (2018).

## 13.3.2 Automated beam optimization at CRYRING@ESR assisted by genetic algorithms

**Authors:** Sabrina Appel, Wolfgang Geithner, Stefan Reimann, all GSI

### Introduction

In recent years, advances in Machine Learning (ML) and related fields of computer science gave rise to a number of software frameworks enabling non-computer scientist to apply this technology for their needs. Within the framework of the FAIR control system, we employed the genetic algorithm JAVA framework "Jenetics" [1] to enhance a control-system end-user application to perform automated multi-parameter optimization of beam-lines. The goal of this is to relieve operating personnel of the time-consuming and tedious task of manual beamline optimization. The technology was applied in simulations of injection schemes of SIS18 [2], now we applied it to the storage ring CRYRING@ESR.

## Beam Optimization Studies at CRYRING@ESR

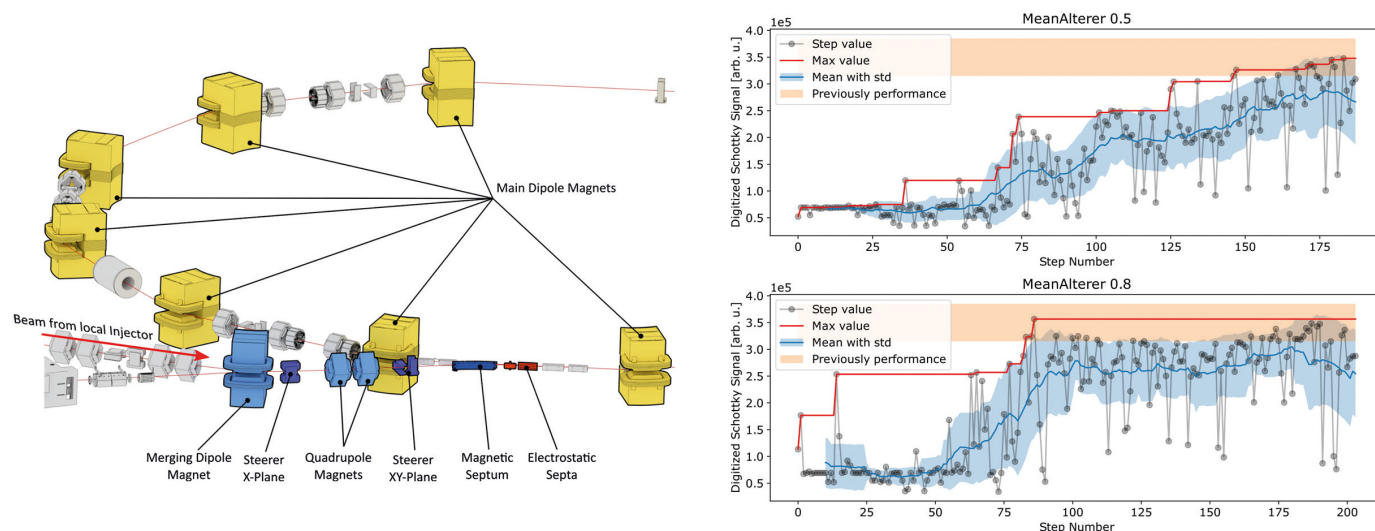


Figure 67. Left: illustration of CRYRING@ESR's devices/parameters controlled by genetic scan algorithm. Right: beam intensity as function of optimization steps with two different algorithm settings. In grey are plotted individual values of each step, red maximum value found by algorithm per optimization "generation". Blue line with bands indicates rolling average value together with standard deviation, orange band illustrates typical beam intensity range achieved by a human operator.

To test the feasibility and performance of the genetic algorithm and to test its "operation readiness", we performed beam-optimization studies on the multi-turn injection system of the FAIR Phase-0 ion storage ring CRYRING@ESR [3]. For this study, a  $H_2^+$  beam with an energy of 300 keV/u from CRYRING@ESR's local injector was injected into the ring. As signal we used the non-destructive "CRY-Radio" signal which is a digitized and pre-processed beam position monitor signal providing a number proportional to the beam intensity in the ring. The genetic algorithm controlled ten parameters of CRYRING's injection system: a dipole in the injection beamline, two magnetic quadrupoles, three steerer magnets, the magnetic septum magnet, two electrostatic septum electrodes and the detuning of the ring's main dipole magnets (see Figure 67, left illustration).

## Results

As can be seen in Figure 67, right figure, the genetic algorithm is able to find beam intensities comparable to those found by a human operator, within typically 100-150 steps, which correspond to about 1 – 1 ½ hours of optimization. Taking this result, this first version of automated beam optimization can be seen as "operations ready". Still, we expect further improvements in terms of reducing the scanning and convergence time by introducing more performant algorithms and by tweaking the control system which was not yet optimized for performance.

## Publications

- [1] **Jenetics - advanced Genetic Algorithm library in JAVA**, online: <http://jenetics.io/>
- [2] Appel, S. ; Geithner, W. ; Reimann, S. ; et al.: **Optimization of Heavy-Ion Synchrotrons Using Nature-Inspired Algorithms and Machine Learning**. In: *Proceedings of the 13th International Computational Accelerator Physics Conference Geneva : JACoW SAPAF02 15-21 p.* (2019), DOI:10.18429/JACOW-ICAP2018-SAPAF02
- [3] Geithner, W. ; Andelkovic, Z. ; Beck, D. ; et al.: **Status and outlook of the CRYRING@ESR project**. 10th International Workshop on Application of Lasers and Storage Devices in Atomic Nuclei Research: "Recent Achievements and Future Prospects" (LASER 2016), LASER 2016, Poznań, Poland, 16 May 2016 – 19 May 2016 *Hyperfine interactions* 238(1), 13 (2017), DOI:10.1007/s10751-016-1383-5



### 13.3.3 Optimization of SIS18 slow extraction spill

Authors: Rahul Singh, Peter Forck, Stefan Sorge, all GSI

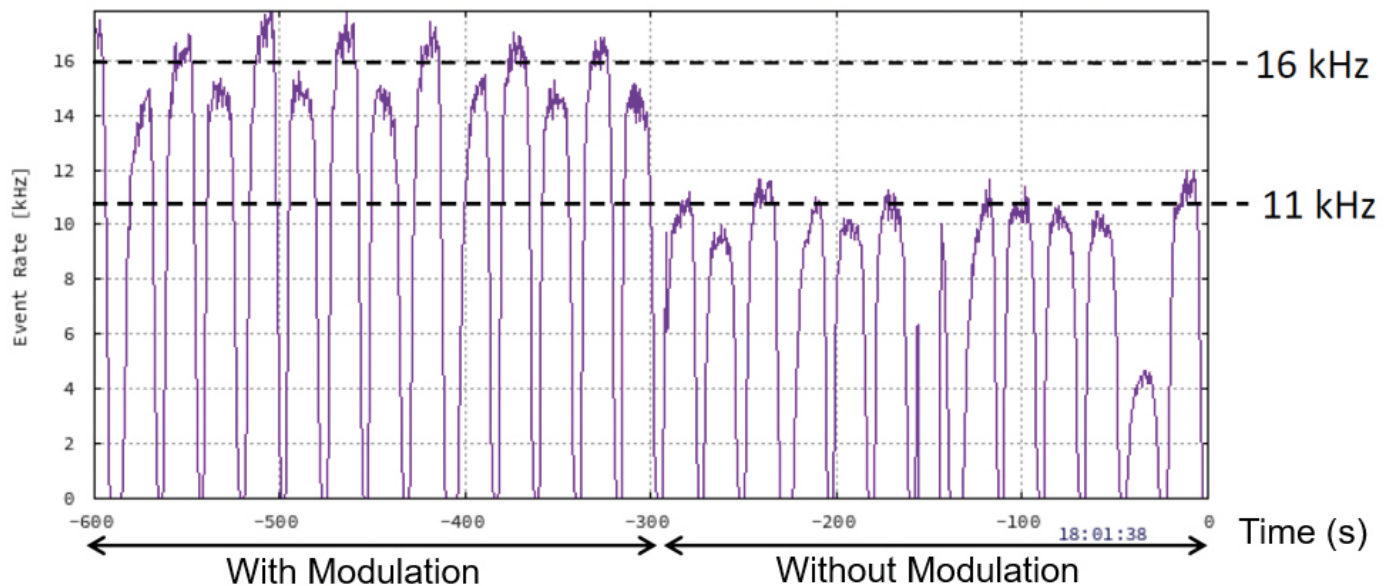


Figure 68. : HADES event rate increase with introduction of the transit time dependent tune modulation technique. (Courtesy: J. Pietraszko and M. Traxler for HADES collaboration)

#### Introduction

The smoothness of micro-spill structure is key for coincidence experiments such as HADES. The micro-spill structure of quadrupole driven slow extraction from SIS-18 is primarily given by the transit time distribution which itself is strongly dependent on the extraction settings. The transit time is defined as the time a particle needs from the instant it leaves the stable phase space area until it is spilled from the synchrotron. The dependence of micro-spill characteristics on transit time distribution were extensively studied in the past year leading to improved settings for slow extraction [1,2]. The improved settings were further augmented with a novel method to control the spill quality when extraction settings could not be further optimized [3]. The usage parameters of this technique referred to as “transit time dependent tune modulation” is presented in this report. The HADES experiment reported an increase of 45% in the event statistics as a result of these efforts.

#### Technique and results

The spill structure is primarily corrupted by the fluctuations on the quadrupole magnets in the order of  $I_n = 5\text{--}15$  mA for a full current of 1.5 kA. The frequency range of the noise current is given by the transit time distribution and is reflected as the “cut-off” frequency ( $f_c$ ) in the spill spectrum. For nominal extraction settings  $f_c \sim 2$  kHz with prominent peaks at the harmonics of 300 Hz. In our technique, an external excitation with frequency  $\sim 3 \cdot f_c$  and amplitude  $I \sim 10 \cdot I_n$  is introduced into the quadrupoles. It suppresses all the lower frequency components by a factor of 3. The introduced frequency itself does not deteriorate the spill since the transit time spread cancels frequencies higher than  $f_c$ . This leads to a significant improvement in the spill quality and directly correlates with the increased event rates for experiments. Figure 68 shows the recorded HADES event rates with and without this technique. Further optimization of amplitude and frequency is ongoing with help of simulations.



## Publications

- [1] R. Singh, P. Boutachkov, P. Forck, et al.: **Observation of SIS-18 spill structure by systematic parameter variations.** In: *GSI Scientific Report 2016, GSI Report 2017-1*, 449 p. (2017).
- [2] Sorge, S. ; Forck, P. ; Singh, R.: **Measurements and Simulations of the Spill Quality of Slowly Extracted Beams from the SIS-18 Synchrotron.** *Journal of physics / Conference Series Conference Series 1067*, 052003 (2018), DOI:10.1088/1742-6596/1067/5/052003
- [3] Preprint Singh, R.; Forck, P.; Sorge, S.: **Smoothing of the slowly extracted coasting beam from a synchrotron.** <https://arxiv.org/abs/1904.09195> (2019).

## 13.3.4 ROSE

Author: Lars Groening, GSI

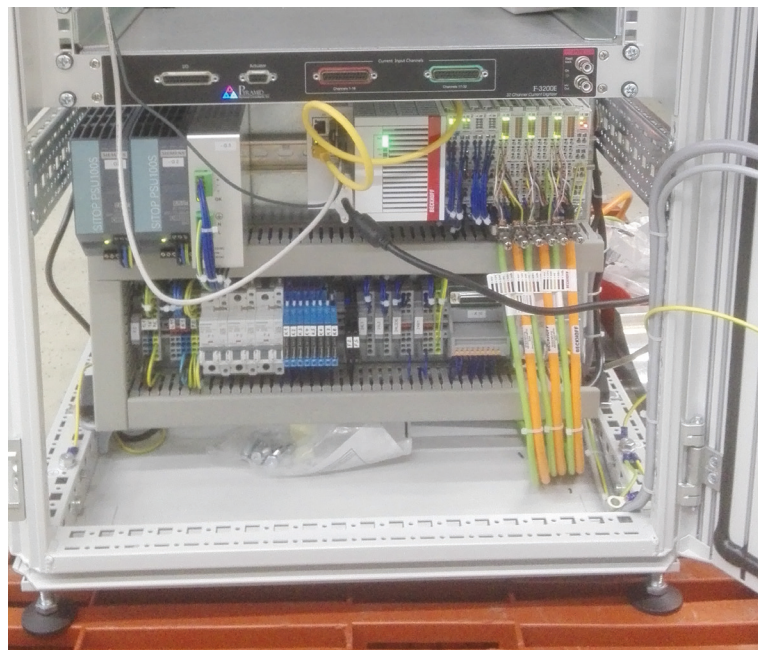


Figure 69. ROBOMAT at NTG. The rack holds the motor drivers, the grid electronics by Pyramid and an industrial PC by Beckhoff on which the software to perform and evaluate the emittance measurements is installed.

The detector system ROSE [1], allowing to perform 4D ion beam emittance measurements independent of the beam energy and time structure, has been built and successfully commissioned in 2016 at GSI in Darmstadt, Germany. This method to measure the four-dimensional emittance has then been granted a patent in 2017 [1]. The inventors together with the technology transfer department of GSI have found an industrial partner to modify ROSE into a standalone, commercially available emittance scanner system. This is a three-step process involving the hardware, 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 achieved progress in the modification of the hardware and the development of the required standalone electronics ROBOMAT.

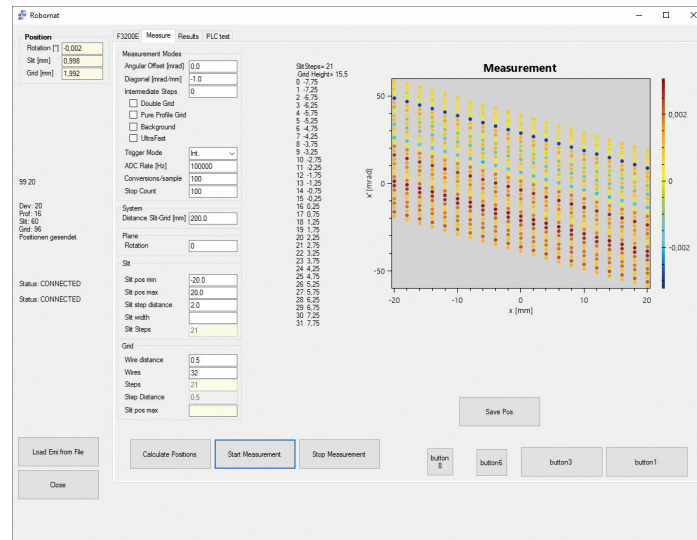


Figure 70. First emittance scan without beam in diagonal mode using ROBOMAT. The background shows systematic deviations as the Pyramid grid electronics had not been calibrated at the time.

The electronics (Figure 69), the software (Figure 70 & Figure 71) and the required hardware modifications on the detector system ROSE have been finished before Christmas and it was possible to run first emittance scans using the complete detector chain.

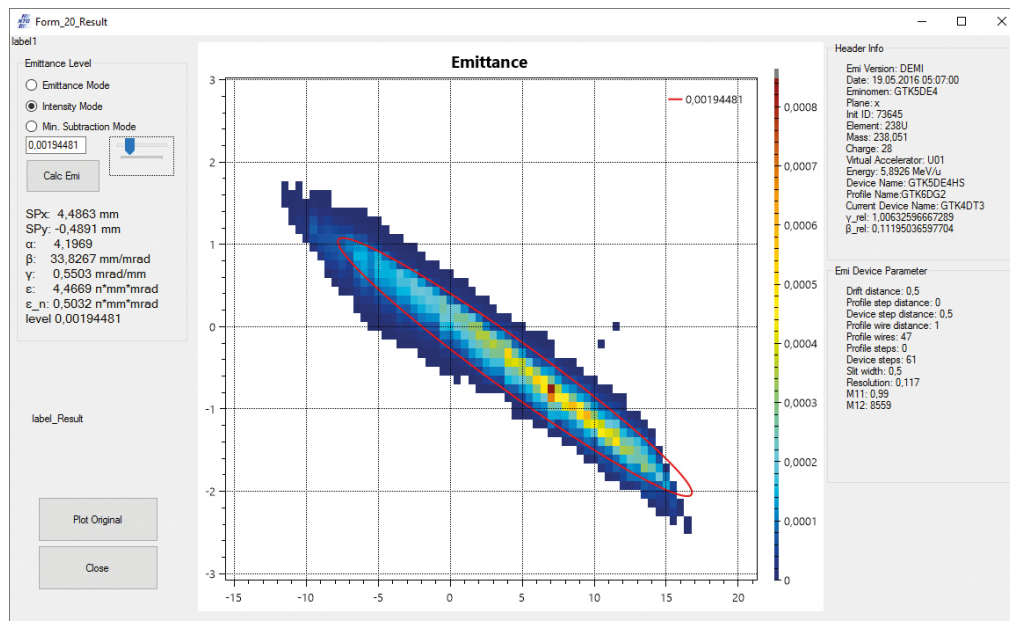


Figure 71. Evaluation of an emittance scan done at GSI using ROBOMAT. This proves that the data format is correct in both directions.

For beam availability, we are still planning to do the site acceptance test at the Ion source test bench of the Heidelberg Ion Therapy facility. Depending on their time schedule we would like to finish before July 2019. Afterwards GSI will possess a fully operational mobile emittance scanner, capable of 2D and 4D emittance scans. Additionally, NTG will have the blueprint and expertise to commercially produce and sell such devices.

The development of the required software package guiding the user through the complicated procedure to perform 4D emittance scans is yet another project of approximately two years. Currently NTG has applied for funding within the Hessen Modell Projekte LOEWE 3: KMU-Verbundvorhaben with GSI as project partner.

## Publications

- [1] Deutsche Patentanmeldung Nr. 102015118017.0 eingereicht am 22.10.2015 beim Deutschen Patent- und Markenamt  
Titel der Patentanmeldung: **Drehmodul für eine Beschleunigeranlage**
- [2] Xiao, C. ; Maier, M. ; Du, X. N. ; et al.: **Rotating system for four-dimensional transverse rms-emittance measurements.**  
*Physical review accelerators and beams* 19(7), 072802 (2016), DOI:10.1103/PhysRevAccelBeams.19.072802

### 13.3.5 Status of the proton injector for FAIR

Authors: Rustam Berezov, GSI; Oliver Delferriere, CEA Saclay; Jerome Fils, GSI; Yannick Gauthier, CEA Saclay; Ralph Hollinger, GSI; Klaus Knie, GSI; Carl-Michael Kleffner, GSI; Oliver Tuske, CEA Saclay

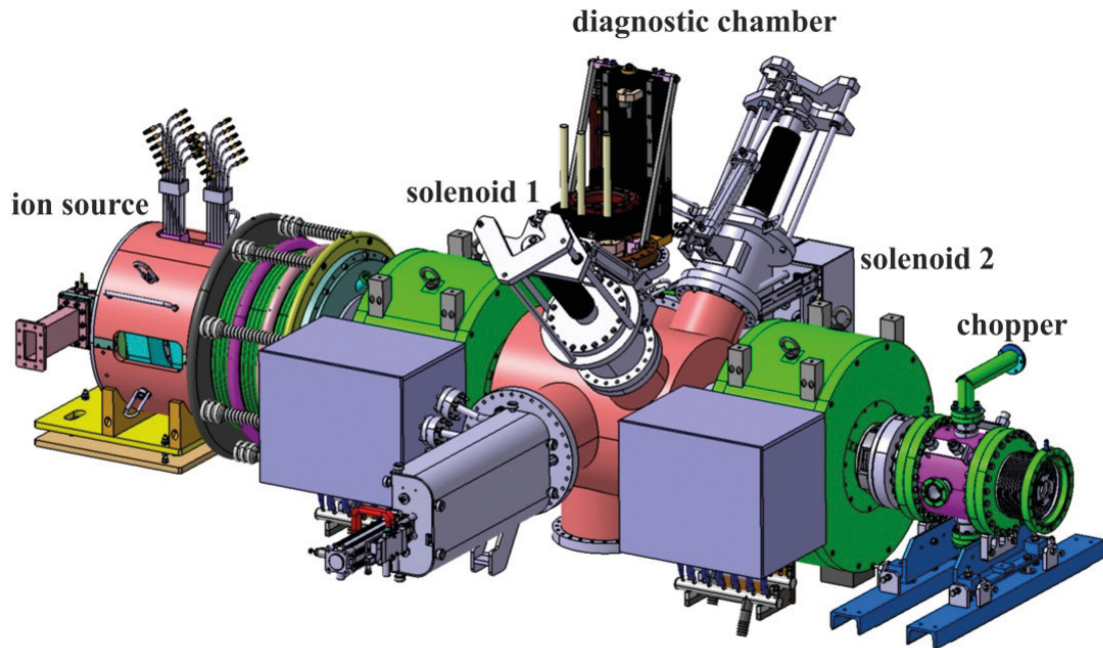


Figure 72. The proton injector for FAIR.

The proton injector for the Facility for Antiproton and Ion Research (FAIR) consists of pulsed 2.45 GHz microwave ion source, a Low Energy Beam Transport (LEBT) and an electrostatic chopper matching the proton beam to the RFQ. The layout of the proton injector is shown in the Figure 72. The ion source is based on Electron Cyclotron Resonance (ECR) plasma production and it has to provide a proton beam at 95 keV energy and up to 100 mA current [1]. The LEBT with two short solenoids system including two magnetic steerers will transport the proton beam into the compact proton linac serving as injector of the upgraded Heavy Ion Synchrotron (SIS18).

The Factory Acceptance Test (FAT) of the high current proton injector has been divided into several commissioning phases [2] and nowadays is on the final stage at CEA/Saclay (France).

During the first phase, measurements of emittance, extracted current and beam composition have been performed for different configurations of ion source parameters such as magnetic field profile, radio frequency power, gas injection and puller electrode voltage behind the extraction system [3]. A highest total extracted ion beam current of around 150 mA has been achieved at the Alternative Current-Current Transformer (ACCT) installed behind the extraction system.

In the second commissioning phase the same measurements were performed in the diagnostic chamber between two solenoids. The highest proton fraction of about 90 % was measured with a Wien filter. This achievement fulfilled the specifications. Emittance measurements as a function of the magnetic field of solenoid 1 were performed as well [4].

In the third phase the beam characterization was done behind the solenoid 2 and an intensity around 100 mA was achieved. Such an intensity was the designed value at the end of the LEBT.



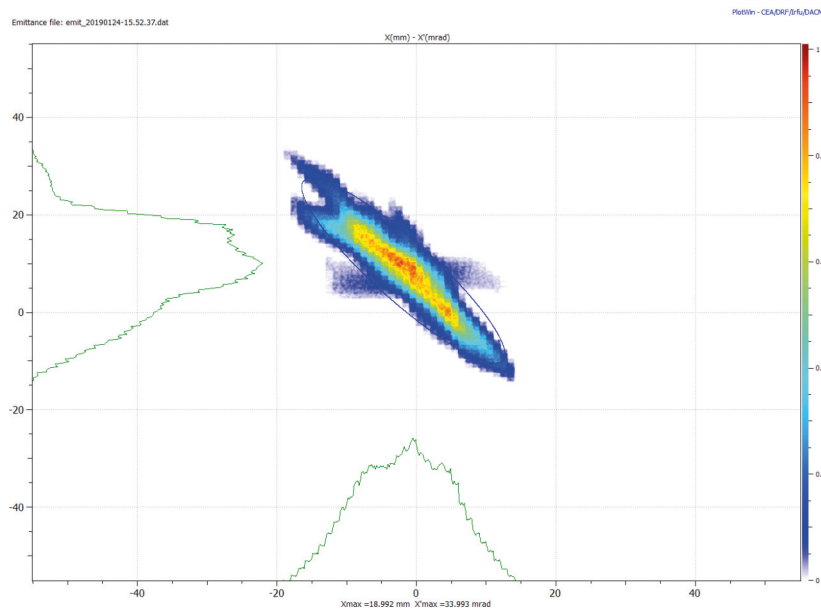


Figure 73. Emittance measurement performed with the Alison scanner behind solenoid 2.

As an example, the emittance measurement performed with an Alison scanner behind solenoid 2 is shown in Figure 73. The measured normalized rms emittance is close to the designed value of 0.3 mm mrad.

However, it was also found that the influence of the magnetic field from Wien filter destroys the space charge compensation in the LEBT and lead to an emittance growth. Therefore, several improvements are necessary in order to use this diagnostic in the LEBT.

Now the last commissioning phase of FAT is running at CEA/Saclay where the chopper chamber with an injection cone is installed.

Within this phase the measurements will be carried out behind the injection cone. It is also planned to perform solenoid field map measurement in order to relate the maximum intensity in the Faraday cup to the emittance and to the twiss parameter at the end of the LEBT for different solenoid values.

The stability of the ion source including beam fluctuation and pulse-to-pulse stability rate will be also tested during the long run test lasting several weeks.

After successful FAT at CEA/Saclay the proton injector will be transported to GSI, Germany, where the final commissioning in the new proton linac building will be performed.

## Publications

- [1] Berezov, R. ; Brodhage, R. ; Chauvin, N. ; et al.: **High intensity proton injector for facility of antiproton and ion re-search.** *Review of scientific instruments* 87(2), 02A705 (2016), DOI:10.1063/1.4932393
- [2] Berezov, R. ; Chauvin, N. ; Clausen, U. ; et al.: **High intensity proton injector for the FAIR p-linac.** In: *Proceedings of the 17th International Conference on Ion Sources, Geneva, Switzerland*, : AIP, AIP Conference Proceedings 2011, 030008 pp., (2018), DOI:10.1063/1.5053269
- [3] Tuske, O. ; Chauvin, N. ; Delferriere, O. ; et al.: **Commissioning of the ECR ion source of the high intensity proton injector of the Facility for Antiproton and Ion Research (FAIR).** *Review of scientific instruments* 89(5), 052303 (2018), DOI:10.1063/1.5017783
- [4] Fils, J. ; Berezov, R. ; Bolzon, B. ; et al.: **Commissioning of the Proton-Linac ECR Source for FAIR.** In: *Proceedings, 23rd International Workshop on ECR Ion Sources (ECRIS2018) : Catania, Italy, September 10-14, 2018* Geneva : JACoW TUP04 p., (2019), DOI:10.18429/JACOW-ECRIS2018-TUP04

### 13.3.6 Development of stochastic cooling system for CR

Authors: Chuan Zhang, Christina Dimopoulou, Axel Bardonner, Roland Böhm, Michael Bräscher, Oleksii Gorda, Rainer Hettrich, Jürgen Krieg, Claudius Peschke, Alexander Stuhl, Stefan Wunderlich, all GSI

#### Introduction

The 1-2 GHz Collector Ring (CR) stochastic cooling system mainly consisting of two cryogenic plunging Pick-Ups (PU), one Palmer PU and two kickers is expected to provide 3D stochastic cooling of coasting secondary beams (antiprotons @  $v = 0.97c$ ; rare isotopes @  $v = 0.83c$ ) from the p-bar target and Super-FRS, respectively. In 2018, further designing, engineering and testing activities have been performed in house or together with external companies in order to meet the challenging project requirements. An overview of the highlights is given.

Power Amplifiers: FoS accepted, series production release



Figure 74. GSI test stand for the SAT of the power amplifiers.

In 2017, the First of Series (FOS) for the 1-2 GHz 250 W power amplifiers was improved with re-designed RF-module for fulfilling the specifications. However, in the Site Acceptance Test (SAT) in Q4/2017, its RF-combiner was burnt after a 16-day test operation. Then, new efforts were made to re-design of the RF-combiner focusing on the reliability issue. Finally, the improved FoS successfully passed the Factory Acceptance Test and a long-time (4-Week) SAT at GSI (Figure 74). In Q4/2018, GSI and the manufacturer

launched the series production.

### Signal Path Optimization from PUs to Kickers

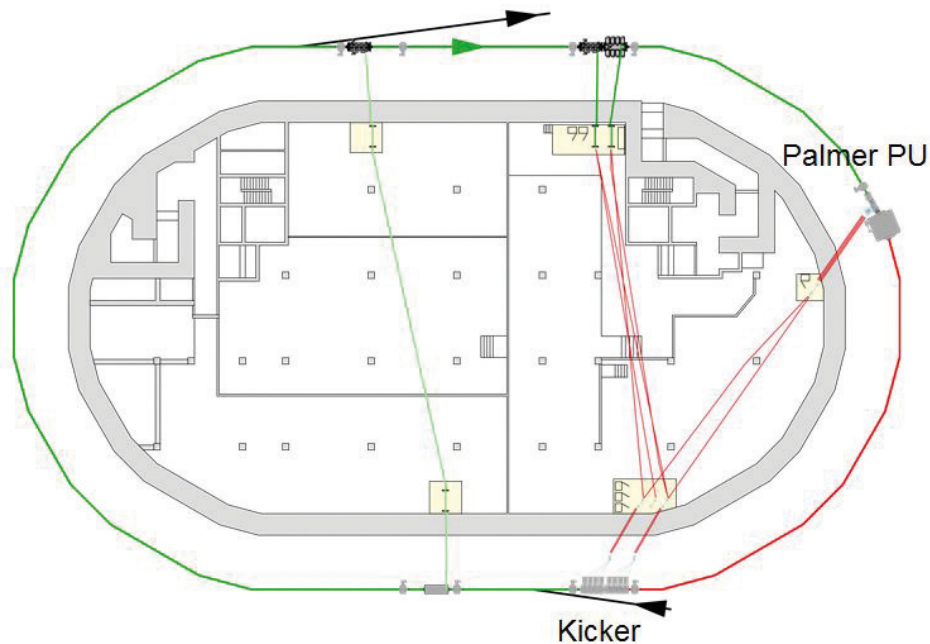


Figure 75. Improved signal path from the PUs to the kickers in the CR building.

There was no reserve for the signal time with respect to the beam flight time from the Palmer PU to the kickers. The particles arrive at the kickers ~30 ns earlier than the signals! Intensive optimization of the signal path from the PUs to the kickers was investigated e.g. by adopting advanced cable materials for the RF signal processing and by changing the position/angle of the holes in the inner wall of the CR building for shortening the signal path. Finally, the new solution provides a safety margin of +7.6 ns and +5.8 ns at the horizontal and vertical kicker respectively. A change request has been submitted to the FAIR Site and Buildings.

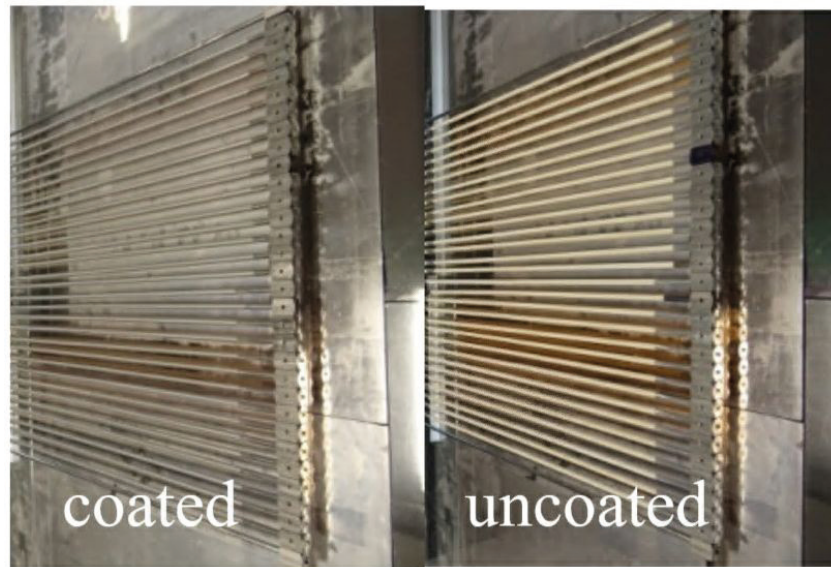


Figure 76. Resistively coated ceramic prototype tubes for damping unwanted microwave modes as needed for CR stochastic cooling.

Other important achievements in 2018 are as follows:

- The specification of the Palmer PU tank has been completed.
- The concept of the microwave damping tubes inside the CR chambers has been presented, and officially accepted. Prototyping activities were successfully carried out with industrial partners (Figure 76). The ferrite microwave absorbers for all PUs have been purchased.
- Tests in the prototype tank of the cryogenic plunging PUs have been prepared. The aim is to verify/consolidate the mechanical assembly, the vacuum/cryogenic performance and the thermal conduction (temperature distribution) inside the complex PU.



## 13.4 Accelerator upgrade

### 13.4.1 Progress on design and construction of the new post-stripper section of the UNILAC

**Authors:** Lars Groening, Xiaonan Du, Manuel Heilmann, Michael S. Kaiser, Sascha Mickat, Carsten Mühle, Markus Romig, Anna Rubin, Vaishnavi Srinivasan, Stephan Teich, Chen Xiao, all GSI

The existing post-stripper section of the UNILAC is in operation since about 45 years. Its design does not match FAIR intensity requirements for heavy ions and the machine failure rate increases from aging. Its replacement with a new Alvarez-section was decided in early 2017.

The production of a First of Series (FoS) cavity section has been started. In parallel a simplified full-scale model of this section has been produced and delivered to GSI in order to serve as "dummy" for testing and optimizing the large components copper plating procedure. After two drift tube prototypes had been fabricated, the production of eleven drift tubes with stems, but w/o internal magnets, for the FoS has started in the GSI workshop. The double walled drift tube with stems comprises various single parts, which are welded together. Special care was taken in developing and defining the welding techniques and sequences with minimum heat load. Unavoidable deformations through welding the single parts together were documented properly. The specification of the FoS quadrupoles inside the drift tubes have been completed. Corresponding field maps to define the proper size of correct field regions and acceptable field errors were derived from beam dynamics simulations. Details on the FoS activities are given in [1].

The definition of the FoS copper plating procedure has been started. In parallel contacts to commercial copper plating facilities have been established successfully in order to have a back-up a provider for plating components of small or inter-mediate dimensions, notably the drift tubes & stem assembly. The FoS shall be tested extensively prior to series production. Former cave Z7 has been chosen as dedicated testing place and the preparation of the site has been started.

Beam dynamics studies on the final drift tube linac DTL design went on. Error studies were extended to the transfer line to the synchrotron (TK) and the error mitigating application of steerers was included. The DTL design was investigated w.r.t. its capability to provide inter-tank energies at low and high beam currents for experiments close to the Coulomb barrier [2]. Simple procedures for the operation of the DTL were defined and it was confirmed that good beam quality can be delivered for the various inter-tank energy scenarios.

Analogue to the existing DTL the new DTL will provide the so-called intermediate energies, which are provided by operating cavities with voltages far below design [3]. For the new DTL these intermediate energies were defined. The beam dynamic studies on intermediate energies were published in NIM A.

The design of the FOS and especially the estimation of resources and time lines for series production were presented to the MAC 20 and received positively. The new DTL design was presented within an invited talk at the Linac 2018 conference [4].

#### Publications

- [1] Heilmann, M. ; Du, X. ; Groening, L. ; et al.: **FoS Cavity of the Alvarez 2.0 DTL as FAIR Injector**. In: *Proceedings, 10th International Particle Accelerator Conference (IPAC2019) : Melbourne, Australia, 19-24 May 2019* Geneva : JACoW MOPTS015 p. (2019), DOI:10.18429/JACOW-IPAC2019-MOPTS015
- [2] A. Rubin et al., Alvarez-DTL beam dynamics simulation, ALV2\_note\_20181203, (2018).
- [3] Xiao, C. ; Rubin, A. ; Groening, L.: **Stable beam operation of drift tube linac cavities at voltages far below design**. *Nuclear instruments & methods in physics research / A Accelerators, spectrometers, detectors and associated equipment*

Section A g28, 70 - 78 (2019), DOI:10.1016/j.nima.2019.03.015

- [4] Mickat, S. ; Du, X. ; Gerhard, P. ; et al.: **Layout of the New FAIR Post-stripper DTL for Intense Heavy Ion Beams**. In: *Proceedings, 29th Linear Accelerator Conference, LINAC2018 : Beijing, China, 16-21 September 2018* Geneva : JACoW TU2A03 p. (2018), DOI:10.18429/JACOW-LINAC2018-TU2A03

## 13.4.2 Operation infrastructure support

**Authors:** Gertrud Walter, Kalliopi Dermati, Markus Romig, Stephan Teich, all GSI

In 2018 manifold operation infrastructure support activities have been carried out by the departments of technology laboratory and mechanics & metalworking. Both departments established a strong collaboration for the use of special welding technologies especially for the construction of different parts and devices for the FAIR accelerators (e.g. p-Linac, SIS 100, etc.) including the Alvarez replacement of the UNILAC. Therefore, in 2018 four welders of the metalworking group have been educated and trained and the related responsible welding supervision has been established within the technology laboratory.

### Technology laboratory:

Besides the daily business, e.g. to support the ion sources to provide Ag-beam, the activities of the Technology laboratory were concentrated on training for and operational implementation of mechanical measurements for quality assurance using a new laser scanner. Measurements using this scanner have been performed e.g. for FAIR-HEBT chambers. In the field of welding, different welding procedures for the construction of drift tubes have been developed, for p-Linac as well as for the UNILAC post-stripper project (Alvarez replacement).

In parallel to these activities, a small number of colleagues of technology laboratory have been working on FEM calculations to support the FAIR project, e.g. the CBM magnets and the SIS100 Lambertson septum.

### Galvanic workshop:

The Galvanic workshop belongs to the department of Technology Laboratory, but it is most important and critical for the Cu electroplating of the UNILAC post-stripper, especially for plating the large-scale tanks. To strengthen the team for that purpose, a further master of electroplating was hired.

In addition, the ladder RFQ of the p-Linac and the so-called "Spillglättungskavität", i.e. a special cavity to smooth out the spill structure of SIS18 was Cu plated (see Figure 77 a), and a collaboration agreement with INFN was settled to Cu plate a few smaller tanks for the ESS project in Sweden. The related activities are part of a mutual agreement between GSI and INFN to support the FAIR project. The practical execution of this agreement started in 2019 and will be reported later on. The ESS activities have been completed by Cu plating also 2 buncher cavities for the Spanish contribution to ESS.

Furthermore, it was necessary to completely revise and set up the chemical composition of the Cu bath because some necessary additive compounds were no longer available from the supplier and therefore had to be replaced by another product. This has been achieved successfully until end of 2018.

In parallel to the operative activities, planning the retrofitting of the Galvanic workshop was continued with special emphasis on the electroplating equipment, such as the large-scale bath tanks and the related peripheral devices, the water handling and acid protection, as well as the chemistry storage devices. Additional planning activities with respect to building measures (mainly fire protection) are ongoing.

## Mechanics and Metalworking:



Figure 77. a) Left side of figure shows the Cu-plated so-called 'Spillglättungskavität' for SIS18, b) on the right side the a first drift tube for the Unilac post-stripper FOS is shown before Cu-plating.

Besides the daily business to support the whole campus, and besides the welding activities already mentioned above, important work has been performed by constructing the new HSI-RFQ to ensure the necessary UNILAC performance for upcoming beam-times. Further significant effort has been made in constructing the drift tubes for the UNILAC post-stripper first of series (FoS, see Figure 77) module and in producing different demo accelerator structures for p-Linac, in both cases including the practical welding activities.

### 13.4.3 Cryo transfer line to the Series Test Facility

Author: Maksym Miski-Oglu, GSI

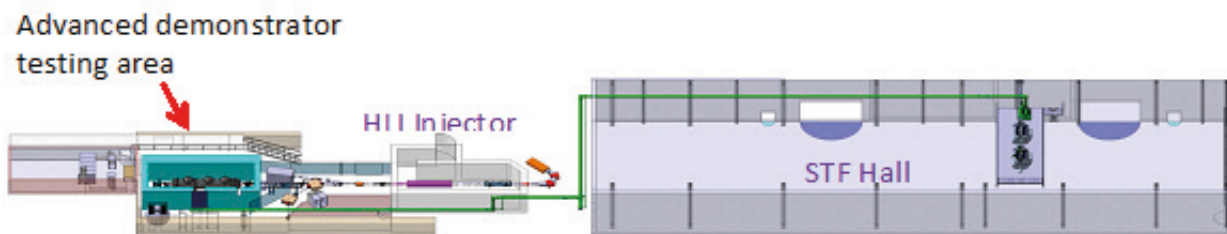


Figure 78. Link to helium supply system at STF.

Recently the first section of a standalone superconducting (sc) continuous wave (cw) heavy ion Linac as a demonstration of the capability of 217MHz multi gap Crossbar H-mode structures (CH) has been commissioned and extensively tested with beam from the GSI High Charge State Injector. As a next step the setup of the first cryomodule – fully equipped with three superconducting acceleration cavities and a rebuncher cavity – is in preparation, as an advanced demonstrator for the cw-Linac to be mounted

at the cw-Linac test area. For the FAIR Project a Series Test Facility (STF) is in operation at GSI. Its main task is to perform the acceptance test for the series production of the superconducting SIS100 dipole magnets. After the magnet testing will be finished, the cryo plant is foreseen for operational supply of the cw- Linac. At present stage of the cw-Linac project the He-distribution system has to be installed to provide the cw-Linac testing area with cold Helium. The additional valve box has to be installed into existing STF He-distribution system. This extension of STF was accomplished by vendor (Cryo World) during Christmas shutdown 2018/2019. After the tendering procedure the contract with an external company (DEMACO, Netherlands) for production and installation of the He-distribution system is signed in December 2018. Since contract start the four-fold vacuum isolated transfer lines and two valve boxes are designed, approved and currently in manufacturing stage. The delivery and installation are scheduled for Q4 of 2019.



## 14. Annex

The publication list of the GSI and of the house publications are available at:  
<https://repository.gsi.de> .de.

### 14.1 Awards

**Prof. Peter Braun-Munzinger**; together with Prof. Johanna Stachel (Univ. Heidelberg) Stern-Gerlach-Medaille 2019 of Deutsche Physikalische Gesellschaft e.V. (DPG) for their experimental works and their contribution to the interpretation of heavy-ion collisions and phase transitions under extreme conditions.

**Prof. Dr. Rudolf Bock**: Semenov medal in gold of the Russian Academy of Science (RAS) for his research on the theory of strongly coupled quantum systems performed at the University Heidelberg and at the ExtreMe Matter Institute EMMI at GSI.

**Prof. Dr. Hannah Elfner (born Petersen)**: Zimányi Medal of Hungarian Academy of Sciences for a theoretical physicist under 40 with international visible research in the field of theoretical high-energy nuclear physics.

**Dr. Christian Graeff**: Günther-von-Pannwitz-Preis of Deutsche Gesellschaft für Radioonkologie e.V. (DEGRO) for his scientific work "Non-invasive cardiac arrhythmia ablation with particle beams".

**Prof. Dr. Yuri Litvinov**: Dunhuang Prize of Chinese Academy of Sciences for his outstanding contributions to the development of precision experiments with stored highly-charged ions at the cooler-storage ring (CSR) in Lanzhou in the province Gansu.

**Prof. Dr. Gisela Taucher-Scholz**: Ulrich-Hagen-Preis of Deutsche Gesellschaft für Biologische Strahlenforschung e.V. for her lifetime achievements in biological radiation research.

#### Awards and prizes for early career researchers

Christoph Schmelzer Award of Verein zur Förderung der Tumorthherapie mit schweren Ionen e.V.: for his Ph.D.: **Dr. Christian Möhler**; for his Ph.D. **Dr. Patrick Wohlfahrt**; for her master thesis: **Tabea Pfuhl** (she got the award of the Walter Greiner Gesellschaft zur Förderung der physikalischen Grundlagenforschung e.V. for the best graduation at the physics faculty at Frankfurt/M university)

FAIR GENCO Award for young scientists of the FAIR-GSI Exotic Nuclei Community (GENCO): **Dr. Yusuke Tsunoda**

Giersch-Excellence-Award of the Stiftung in cooperation with the graduate school HGS-HiRe for Ph.D. theses: **Dr. Björn Borm**, **Dr. Volodymyr Vovchenko**, **Dr. Alba Soto Ontoso** (all from Goethe University Frankfurt) and **Dr. Julius Gronefeld**, **Dr. Alexander Tichai**, **Dr. Olga Sokol** (all from Technische Universität Darmstadt)

PANDA PhD Prize of the PANDA Collaboration **Dr. Mustafa Schmidt**; PANDA Theory PhD Prize of the PANDA Collaboration **Dr. Antje Peters**

Walter Greiner Gesellschaft zur Förderung der physikalischen Grundlagenforschung e.V. award for the best graduation at the physics faculty at Frankfurt/M university: **Tabea Pfuhl**

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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.

