HIM

HELMHOLTZ
Helmholtz Institute Mainz

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HIM Activity Report 2021

1. HIM Facts & Figures

Personnel and Funding

Personnel

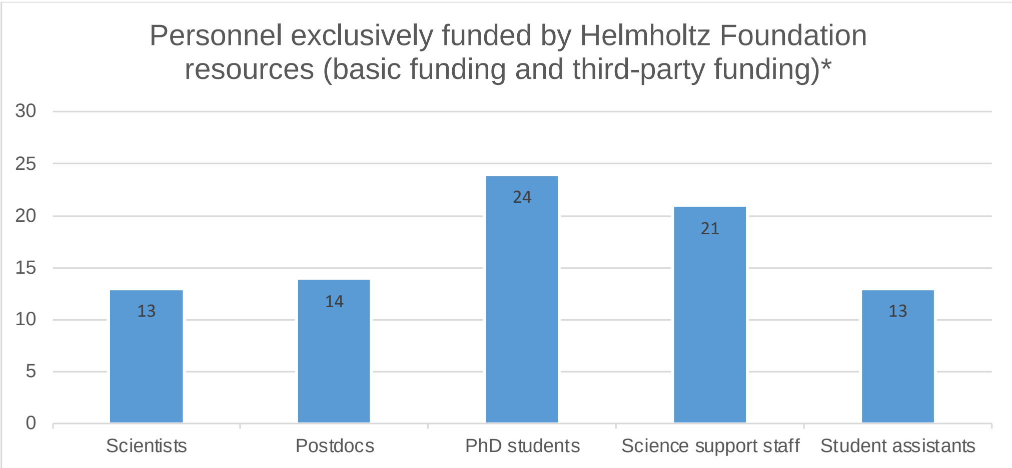

Fig. 1: Headcount as of 31.12.2021
* Personnel from other third-party funding is not included;
Section Heads and PIs are funded mainly through the contribution of the Johannes Gutenberg-. Universität Mainz and are not included here.

Basic funding

Basic funding by Helmholtz Foundation 2021: 6.589.000 €

Within the PoF-IV period 2021-2027, there is an annual increase of 2 %.

Third Party funding

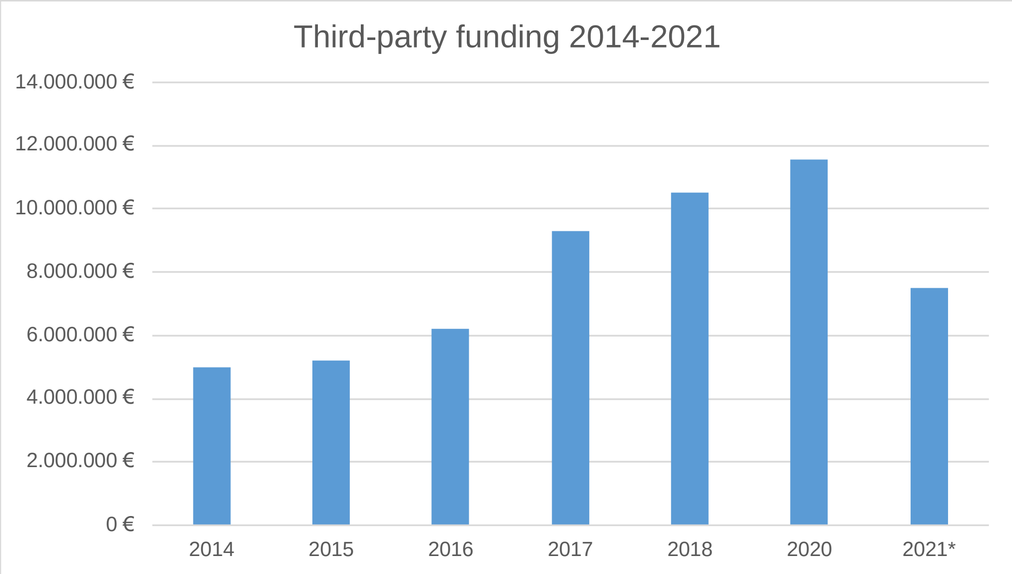

Fig. 2: Third-party funding 2014-2021
* In addition, HIM is part of the PRISMA+ Cluster of Excellence with 12 PIs (funding 2021: 7.2 million €, PIs: 49).

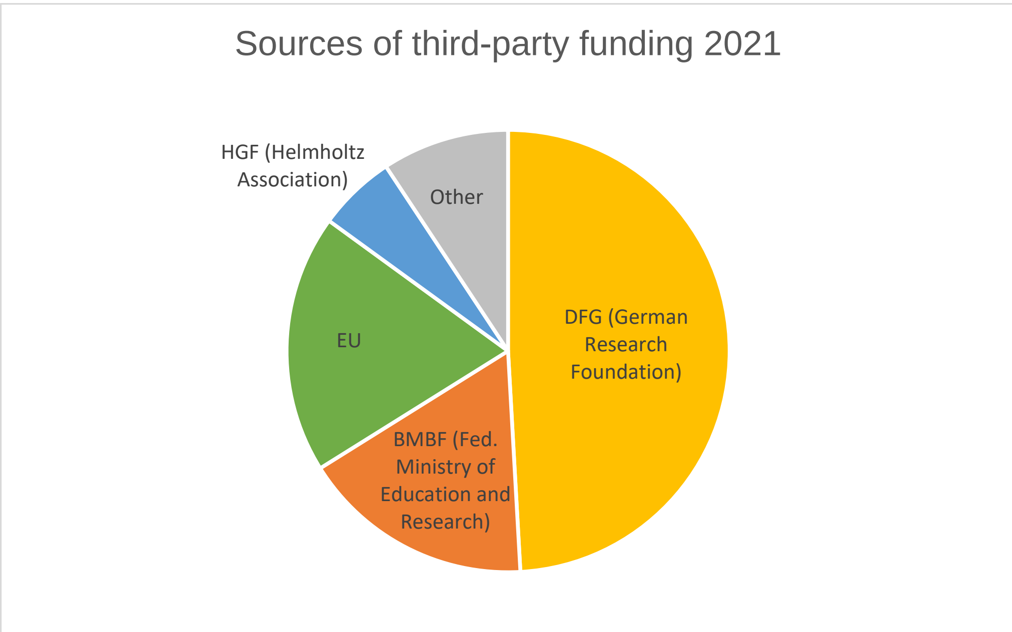

Fig. 3: Sources of third-party funding 2021

Visiting Scientists

Prof. Dr. Maarten Boonekamp
CEA Paris-Saclay, France
HIM Visiting Scientist Program
08/2021 – 07/2022

Prof. Dr. Henryk Czyz
University of Silesia, Poland
HIM Visiting Scientist Program
09/2021 – 10/2021

Prof. Dr. Michael Gericke
University of Manitoba, Canada
10/2021

Prof. Dr. Miroslav Iliaš
Matej Bel University Banská Bystrica, Slovakia
HIM Visiting Scientist Program
06/2021 – 09/2021

Prof. Dr. Krishna S. Kumar
University of Massachusetts Amherst, USA
10/2021

Awards

Prof. Dr. Dmitry Budker, Dr. Danila Barskiy, Dr. John Blanchard, Dr. James Eills
Erwin Schrödinger Prize 2021

Simon Lauber
Giersch Excellence Grant 2021

Julian List
Giersch Excellence Grant 2021

Prof. Dr. Frank Maas
Senior Member of the Gutenberg Academy, 10/2021

Dr. Oliver Noll
PANDA PhD Prize 2021

PhD Theses

Completed theses, supervised by HIM scientists

B. Andelic,
Direct mass measurements of No, Lr and Rf isotopes with SHIPTRAP and developments for chemical isobaric separation

G. Chatzidrosos,
A perfect imperfection: Quantum magnetometry and applications using nitrogen-vacancy defects in diamond

B. Gläser,
Aufbau des Elektronen-Taggers zur Erweiterung des A4-Experiments für Messung der paritätsverletzenden Elektron-Proton-Streuung unter Rückwärtsstreuwinkeln

P. Heil,
Kohärente Smith-Purcell-Strahlung zur minimal invasiven Bunchlängenmessung im Subpikosekundenbereich

Y. Hu,
Non-contact diagnostic methods based on optically pumped magnetometers

B. Ledroit
Target Induced Halo Formation and Collimation Following MAGIX at MESA

C. Matejcek,
Strahldynamik der Niederenergie-Strahlführung von MESA unter Berücksichtigung von Raumladung und Multipol-Beiträgen höherer Ordnung

A. Risch,
Isospin breaking effects in hadronic matrix elements on the lattice

C. Rosner,
Measurement of the Timelike Electromagnetic Form Factors of the Proton at the BESIII Experiment through the Process $e^+e^-\rightarrow p\bar{p}$

D. Simon
Gesamtkonzept für den MESA-Teilchenbeschleuniger unter besonderer Berücksichtigung von Strahloptik und Kryogenik

A. Steinberg,
Photon production and screening properties of the QGP from lattice QCD

K. Zapp,
A study of spectral functions in lattice QCD

H. Zheng,
Novel magnetic-sensing modalities with nitrogen-vacancy centers in diamond

Conferences organized/supported

721. WE-Heraeus-Seminar: Light Dark Matter Searches, 08-11 June 2021 (online)

18th Workshop on Recoil Separator for Superheavy Element Chemistry (TASCA21), Darmstadt, Germany, 21 -23 June 2021 (online)

The IX International Symposium “Modern Problems of Laser Physics” and International School on Laser Physics ant Photonics for Young Scientists (MPLP-2021), Novosibirsk, Russia, 23-31 August 2021

International Physics School on Muon Dipole Moments and Hadronic Effects, 30 August – 02 September 2021 (online)

Particles and Nuclei International Conference (PANIC2021), Lisbon, Portugal, 05-10 September 2021 (online)

2nd Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar 2021/2022, October 2021 – March 2022 (online)

Workshop “Particle & AMO Physicists discussing Quantum Sensors and new Physics”, Munich, Germany, 06-17 December 2021

2. Selection of Invited Conference Talks

ACID

K. Aulenbacher, Scalable HV-Modules for a Magnetized Relativistic Electron Cooler,
13th International Workshop on Beam Cooling and Related Topics (COOL'21), Novosibirsk, Russia, 01-05 November 2021 (online)

W. Barth, Commissioning of normal and super-conducting LINACs at GSI,
Experiences during Hadron LINAC Commissioning, ARIES-Workshop, 25-29 January 2021 (online)

M. Basten, H-Mode Cavity Development
HBS-Innovationspool Meeting, Jülich, Germany, 28 April 2021 (online)

S. Lauber, Studies on the Reconstruction of the 6D Phase Space,
GSI Accelerator Seminar, Darmstadt, Germany, 04 November 2021 (online)

EMP

L. Capozza, FAIR Phase-0 at MAMI,
PANDA Collaboration Meeting 21/1, 08-12 March 2021 (online)

A. Dbeyssi, Study of the nucleon structure with the PANDA experiment at FAIR,
Particles and Nuclei International Conference (PANIC2021), Lisbon, Portugal,
05-10 September 2021 (online)

A. Dbeyssi, The PANDA experiment at FAIR,
Mass in the Standard Model and Consequences of its Emergence, ECT*-Workshop, Moscow, Russia, 19-23 April 2021 (online)

A. Dbeyssi, The PANDA experiment at FAIR
20th Lomonosov Conference on Elementary Particle Physics, Moscow, Russia,
19-25 August 2021 (online)

D. Liu, Study of Φ(2170) at BESIII,
European Physical Society Conference on High Energy Physics (EPS-HEP), Hamburg, Germany, 26-30 July 2021 (online)

F. Maas, The exciting physics program of the PANDA-Experiment at FAIR,
NICA SPD Collaboration Meeting, JINR, Dubna, Russia, 08-10 June 2021 (online)

O. Noll, Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter,
PANDA Collaboration Meeting 21/3, 25-29 October 2021 (online)

S. Wolff, FAIR Phase-0 PANDA: Messung der Pion-Übergangsformfaktoren in der virtuellen Primakoff-Kinematik,
MU Days, Karlsruhe, Germany, 24-25 November 2021 (online)

MAM

D. Antypas, Precision isotope shifts in ytterbium and implications for new physics,
16th Marcel Grossmann Meeting, Rome, Italy, 05-10 July 2021 (online)

D. Barskiy, SABRE-based hyperpolarization of [15N, U-13C]-butyronitrile “nuclear spin chain” at ultralow magnetic fields,
International hyperpolarization conference (HYP21), Lyon, France, 05-09 September 2021

D. Budker, Magnetic Sensing with NV Centers and Zero-field NMR,
OIST Mini-Symposium for Quantum Sensors of Magnetic and Inertial Forces, Okinawa, Japan, 01 March 2021 (online)

D. Budker, Nowhere to hide: Some new Ways to search for Dark Matter,
Physics Colloquium, Padova, Italy, 25 February 2021 (online)

A. Wickenbrock, The spectral lineshape of gradient-coupled bosonic dark matter in our galaxy,
16th Patras Workshop on Axions, WIMPs and WISPs, Triest, Italy, 14-18 June 2021

SHE

M. Block, Laser Spectroscopy and Mass Spectrometry of the Heaviest Element at GSI,
27th Nuclear Physics Workshop, Lublin, Poland, 21-23 October 2021

M. Block, Properties of exotic nuclei revealed by laser spectroscopy,
Scientific Colloquium Webinar RESANET (Réactions, structure et Astrophysique Nucléaires: Expériences et Théories), 22 November 2021 (online)

M. Block, Superheavy Element Research at GSI,
DPG-Tagung 2021 der Sektion Materie und Kosmos, 30 August – 03 September 2021 (online)

J. Khuyagbaatar, Island of the stability: back to the future,
Virtual SHE seminars, National Centre for Nuclear research (NCBJ), Świerk, Poland, 13 April 2021 (online)

S. Knecht, Shedding light on the chemistry of (super-)heavy elements with electronic structure theory,
International Symposium on Correlated Electrons (SymCorrel21), Munich, Germany, 05-07 October 2021

SPECF

P. Achenbach, Dark matter search with the DarkMESA electron beam-dump experiment,
Particles and Nuclei International Conference (PANIC2021), Lisbon, Portugal,
05-10 September 2021 (online)

A. Denig, Outlook Talk: Status of g-2 problem,
16th International Workshop on Meson Physics, Warsaw, Poland, 17-20 May 2021 (online)

J. Pochodzalla, Hypernuclei and hyperons at FAIR – Introduction,
12th FAIR and GSI Joint Scientific Council, Darmstadt, Germany, 11 October 2021

J. Pochodzalla, Overview – Hypernuclei and Hyperatoms,
EXA online conference 2021, Vienna, Austria, 13-17 September 2021 (online)

J. Pochodzalla, Strange Systems at PANDA
Hadron In Nucleus 2020, Kyoto, Japan, 08-10 March 2021

THFL

S. Bacca, CEvNS Overview,
Snowmass21 NF06 Low Energy Neutrino and Electron Scattering Workshop,
12 November 2021 (online)

D. Djukanovic, Recent Progress on Nucleon Form Factors,
38th International Symposium on Lattice Field Theory, ZOOM/GATHER@MIT,
26-30 July 2021 (online)

J. Erler, Global vision of precision measurements,
55th Rencontres de Moriond on Electroweak Interactions and Unified Theories,
21-27 March 2021 (online)

H. B. Meyer, Vector spectral functions of the quark-gluon plasma,
Tackling the real-time challenge in strongly correlated systems: spectral properties from
Euclidean path integrals, ECT workshop, 13-17 September 2021 (online)

H. Wittig, The Standard Model Prediction for the muon g-2,
Phenomenology 2021 Symposium, Pittsburgh, USA, 24-26 May 2021 (online)

3. Highlight Publications

ACID

K. Aulenbacher et al.,
Scalable HV-Modules for a Magnetized Relativistic Electron Cooler,
In: **Proceedings of the 13th International Workshop COOL 2021, Novosibirsk, Russia, 01-05 November 2021, 31-32**

T. Beiser et al.,
Observation of Beam Induced Fluorescence (BIF) at the Electron Cooler Test Bench at Helmholtz-Institut Mainz (HIM),
In: **Proceedings of the 13th International Workshop COOL 2021, Novosibirsk, Russia, 01-05 November 2021, 33-35**

P. Heil et al.,
Coherent Smith-Purcell radiation for minimally invasive bunch length measurement at the subpicosecond time scale,
Phys. Rev. Accel. Beams 24, 042803 (2021)

S. Lauber et al.,
A dynamic collimation and alignment system for the Helmholtz linear accelerator,
Rev. Sci. Instr. 92, 113306 (2021)

R. Singh et al.,
Comparison of Feschenko BSM and Fast Faraday Cup with Low Energy Ion Beams,
In: **Proceedings of the 10th International Beam Instrumentation Conference, IBIC 2021, Pohang, Korea, 13-17 September 2021, 407-411**

EMP

G. Barucca et al.,
PANDA Phase One,
Eur. Phys. J. A 57, 184 (2021)

G. Barucca et al.,
"Feasibility studies for the measurement of time-like proton electromagnetic form factors from $\bar{p}p \to \mu^+\mu^-$ at PANDA at FAIR",
Eur. Phys. J. A 57, 20 (2021)

The BESIII Collaboration,
Oscillating features in the electromagnetic structure of the neutron,
Nat. Phys. 17, 1200-1204 (2021)

BESIII Collaboration,
Measurement of proton electromagnetic form factors in the time-like region using initial state radiation at BESIII,
Phys. Lett. B 817, 136328 (2021)

A. Dbeyssi et al.,
Investigation on intense axial magnetic field shielding with a large melt cast processed Bi-2212 tube,
arXiv:2205.00727 (submitted in May 2022)

MAM

D. Aybas et al.,
Quantum sensitivity limits of nuclear magnetic resonance experiments searching for new fundamental physics,
Quantum Sci. Technol. 6. 034007 (2021)

D. Kim,
A machine learning algorithm for direct detection of axion-like particle domain walls,
arXiv:2110.00139 (submitted in October 2021)

J. E. Albert et al.,
A precise photometric ratio via laser excitation of the sodium layer – I. One-photon excitation using 342.78 nm light,
Monthly Notices of the Royal Astronomical Society 508, 4399-4411 (2021)
A precise photometric ratio via laser excitation of the sodium layer – II. Two-photon excitation using lasers detuned from 589.16 and 819.71 nm resonances,
Monthly Notices of the Royal Astronomical Society 508, 4412-4428 (2021)

P. Put et al.,
Zero- to Ultralow-Field NMR Spectroscopy of Small Biomolecules,
Anal. Chem. 93, 3226-3232 (2021)

R. Zhang et al.,
Stand-Off Magnetometry with Directional Emission from Sodium Vapors,
Phys. Rev. Lett. 127 (2021), 173605

SHE

J. Khuyagbaatar et al.,
Spontaneous fission instability of the neutron-deficient No and Rf isotopes: The new isotope ^{249}No,
Phys. Rev. C 104, L031303 (2021)

A. Såmark-Roth et al.,
Spectroscopy along Flerovium Decay Chains: Discovery of ^{280}Ds and an Excited State in ^{282}Cn
Phys. Rev. Lett. 126, 032503 (2021)

E.V. Kahl et al.,
Ab initio calculations of the spectrum of lawrencium
Phys. Rev. A 104, 052810 (2021)

A. Yakushev et al.,
First Study on Nihonium (Nh, Element 113) Chemistry at TASCA
Front. Chem. 9, 753738 (2021)

V. Pershina et al.,
Reactivity of the Superheavy Element 115, Mc, and Its Lighter Homologue, Bi, with Respect to Gold and Hydroxylated Quartz Surfaces from Periodic Relativistic DFT Calculations: A Comparison with Element 113, Nh
Inorg. Chem. 60, 9896-9804 (2021)

SPECF

G. Barucca et al.,
The potential of Λ and Ξ^- studies with PANDA at FAIR,
Eur. Phys. J. A 57, 154 (2021)

M. Yoshimoto et al.,
First observation of a nuclear s-state of a Ξ hypernucleus, ${}^{15}_{\Xi}\mathrm{C}$,
Prog. Theor. Exp. Phys. 2021, 073D02 (2021)

G. Barucca et al.,
PANDA Phase One,
Eur. Phys. J. A 57, 184 (2021)

M. Ablikim et al. (BESIII Collaboration),
Measurement of the Cross Section for $e^+e^- \rightarrow$ Hadrons at Energies from 2.2324 to 3.6710 GeV,
Phys. Rev. Lett 128, 062004 (2022)

M. Lauß et al.,
Electron beam studies of light collection in a scintillating counter with embedded fibers,
Nucl. Instr. Meth. A 1012, 165617 (2021)

THFL

O. Deineka et al.,
Dispersive analysis of the $\gamma\gamma \rightarrow D\bar{D}$ data and the confirmation of the $D\bar{D}$ bound state,
Phys. Lett. B 827, 136982 (2022)

E.-H. Chao,
Hadronic light-by-light contribution to $(g-2)_\mu$ from lattice QCD: a complete calculation,
Eur. Phys. J. C 81, 651 (2021)

M. Cè et al.,
Vacuum correlators at short distances from lattice QCD,
J. High Energ. Phys. 2021, 215 (2021)

J. R. Green et al.,
Weakly bound H Dibaryon from SU(3)-Flavor-Symmetric QCD
Phys. Rev. Lett. 127, 242003 (2021)

S. Malbrunot-Ettenauer et al.,
Nuclear Charge Radii of the Nickel Isotopes ${}^{58\text{-}68,70}\mathrm{Ni}$,
Phys. Rev. Lett. 128, 022502 (2022)

4. Activities of the HIM Research Sections

Section ACID: Accelerator Design and Integrated Detectors

Kurt Aulenbacher and Winfried Barth

ACID1

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

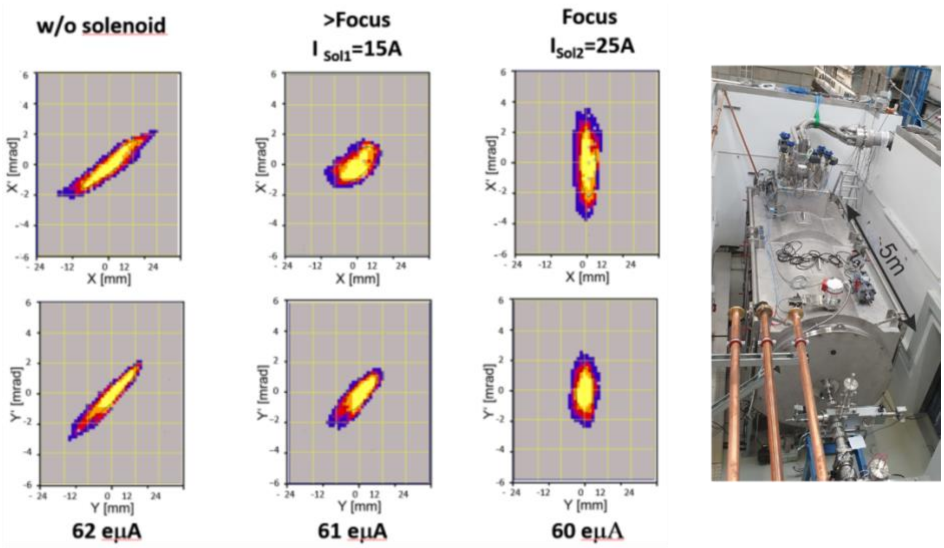

Fig. 4: Measured Ar^{8+} beam emittance at CM1 (left); the photograph (right) shows the installed cryostat during test beam time 2021.

For longitudinal beam matching, each cryomodule (CM) is equipped with a superconducting 217 MHz single-spoke buncher cavity. The production of the first two buncher cavities, designed for a particle velocity of $\beta = 0.07$ for CM1 and CM2, already started in 2020. In 2021, the welding work on the cavities was successfully completed. In this phase, all production steps were carried out on the basis of detailed RF and structural-mechanical simulations in cooperation with the manufacturer in order to achieve the target frequency of the cavities. In December 2021, the cavities were ready for the final surface preparation, which includes several chemical etching steps, a 650 °C bakeout for 24 hours, and high-pressure rinsing with ultrapure water. The surface treatment is scheduled for completion in early 2022. So far, all frequency-influencing effects during the manufacturing process, such as welding shrinkage, pressure sensitivity, and thermal shrinkage have been successfully verified with corresponding simulations. In order to bring the power couplers for the superconducting RF cavities of the HELIAC to the series-production stage, a number of tests were carried out. In a high-power test, the performance of the coupler was confirmed for up to 5 kW of forwarded RF-power in cw-mode. During the test, different operating and conditioning procedures were developed and tested. After successful completion of the RF tests, the coupler was integrated into the first HELIAC-cryomodule CM1 and subjected to further tests. In this context, the static heat load and the temperature gradient of the coupler was determined. Furthermore, the dynamic heat load applied to the cryo-system, caused by ohmic losses of the power coupler, was also measured. The results of this test campaign agree very well with the associated simulations and promise a successful and reliable operation of the cavities.

Parallel to the activities mentioned above, the corresponding beam dynamics layout for the injector part of the HELIAC has been revised for integration into a standalone machine housed in a separate linac tunnel. An ECRIS (Electron Cyclotron Resonance Ion Source) together with an RFQ (Radio Frequency Quadrupole) will supply a beam with $A/Z \leq 6$ to a normal conducting IH (Interdigital H-mode) pre-accelerator unit, providing for beam-energy gain from 300 keV/u to 1400 keV/u. The revision of the injector linac allows redesigning the IH cavity using an APF (Alternating Phase Focusing) beam-dynamics scheme in order to yield two quadrupole-lens free cavities and to extend the injector with further beam diagnostics and beam steerers. Due to this advanced DTL linac layout, a beam with low emittance growth will be delivered and thus flexible cw operation is ensured. The beam dynamics, RF and thermal design of the APF cavities is already finalized and tendering of the cavities is imminent. Besides, the purchasing of the next generation of CH-cavities – CH3-CH5 sufficient to serve for CM2 and CH6-CH8 for CM3 – is delayed by more than 15 months, caused by different funding issues among others related to the Ukraine conflict. Since Q4/2021 the intensive installation phase has been started to prepare the Advanced Demonstrator cryomodule (CM1) for the four-week commissioning beam time at GSI in June 2022. Meanwhile CM1 has been transported to the HIM-cleanroom – disassembly of the coldstring is envisaged at next.

ACID2

ACID2 has received the high-voltage tank for the 1.2 MeV HESR magnetized cooler prototype in spring 2021. The first 600 kV stage, which was designed by the Budker Institute in Novosibirsk, is now installed in the tank. During the reporting period we have developed a pneumatic system for driving the turbine operating on the HV-terminal. This was achieved in cooperation with Manfred Wirsum from the Institute of Turbomechanics at RWTH Aachen. The analysis shows that stable operation can be obtained over a wide range of power loads and that the two required turbines – each powering the solenoid focusing system of a 600 kV stage – can be driven by the existing compressor. This approach takes into account the boundary conditions given by piping and the distances in the HIM experimental hall. The remaining parts for the pneumatic circuit – mainly additional buffer tanks, a heat exchanger, and valves for flow control – are presently being ordered. Because of the political crisis since February 2022, the delivery of the second stage from the Budker Institute – which was supposed to happen in March this year – is shifted indefinitely. We have therefore intensified our attempts to find alternative applications for our device. The most promising approach at the moment is to use it in the context of micro-beam radiation therapy. This new approach to cancer therapy requires generation of an electron beam line focus with high aspect ratio, about 60 μm*15 mm. Improved beam power handling is achieved by the high aspect ratio, since heat transfer in the direction of the short axis is governed by the speed of the excited electrons in the material and not, as usually the case in heat transfer problems, by phonons which travel at orders of magnitude lower speed. For the specific case of the line focus, the long-standing limitations of Xray tubes can therefore be surpassed. This serves to obtain high intensity Xray microbeams behind a multi-slit collimator. Our group has designed such a 300 kV, 0.3 A (90 kW) system for a preclinical prototype which is currently under construction at the Technical University of Munich. The extreme aspect ratio is obtained by using a relatively conventional barium dispenser cathode with a line shape. The aspect ratio is further amplified by using quadrupoles. The simulations indicate that the required beam brightness in the focal line can be achieved in spite of relatively strong space charge. Since a 600 kV, 2.5 A (1.5 MW) beam is envisaged for a real therapeutic device, our apparatus at HIM can play a role in this development, since it is designed for beams in that power region, albeit with energy recovery. In order to reduce radiation protection issues, we have proposed to use low duty cycle nanosecond pulses which are demanded in order to calibrate dosimetry. Our work concerning minimal invasive beam diagnostics of high-power electron beams has seen considerable progress. It is performed by a PhD student using the 30 kV electron cooler test stand in HIM. A cooled CCD camera, which has single-photon-counting capabilities, was used. In another experiment, an optical spectrometer was used which allowed identifying the spectral lines resulting from the excitation of the excited gas molecules in the beam path. This device yields information of beam parameters of high-power DC-beams (here 9 kW) without interfering with them, the optical signals are detectable even in an ultra-high vacuum of only a few times 10^{-10} mbar.

Section EMP: Electro-Magnetic Processes

Frank Maas

Analysis of BESIII data

The analysis of BESIII data to extract the proton time-like form factors from initial state radiation has been the topic of the PhD thesis of D. Lin. It has been reported and submitted in 2020. It has been published in 2021 [BESIII Collaboration, Phys. Lett. B 817, 136327 (2021)]. The PhD theses work of Paul Larin and Samer Ahmed, namely the analysis of the energy scan data taken in 2015 for the neutron form factor in the time-like region between 2.0 GeV and 3.08 GeV, was reported in 2020 and has been published in 2021 too [The BESIII Collaboration, Nat. Phys. 17, 1200-1204 (2021)]. Moreover, we have been able to submit three review articles in a special issue of the journal Symmetry; they appeared early 2022.

We have used the energy scan data between 2.0 GeV and 3.08 GeV taken in 2015 with the BESIII experiment in order to analyse the process $e^+e^- \rightarrow \bar{\Delta}\Delta$ and $e^+e^- \rightarrow \Lambda\bar{\Sigma}_0$. A memo summarizing both analyses has been reviewed by the BESIII collaboration, a draft for a publication is in progress. Similarly, for the process $J/\psi \rightarrow \overline{\Sigma_0}\Sigma_0$ the analysis of the line shape has been used to extract the phase between the EM and strong amplitude.

Feasibility studies of EMP-processes at the future PANDA-experiment

The measurement of the proton form factors in the time-like region using the $\bar{p}p \rightarrow e^+e^-, \mu^+\mu^-$ annihilation reactions has been reported in 2020; the manuscript has been published in 2021 [G. Barucca et al., Eur. Phys. J. A 57, 30 (2021)]. The analysis of the $\bar{p}p \rightarrow e^+e^-\pi^0$ reaction has been further progressed with the aim to achieve complementary measurements of the proton form factors at PANDA in a region that has never been experimentally accessed. The cross section has been calculated for extracting time-like form factors below threshold (at lower energy and momentum transfer) or Transition Distribution Amplitudes at higher energies and momentum transfer. These processes have been included in the software framework. PANDA is expected to provide first measurements of the proton electromagnetic form factors below threshold.

In addition, the “PANDA Phase One”-paper was published in 2021 [G. Barucca et al., Eur. Phys. J. A 57, 184 (2021)]. Alaa Dbeyssi from EMP is convener of the working group studying the physics of “electromagnetic processes” within the PANDA collaboration. The results show that PANDA will improve the precision of the proton-form-factor measurements for $q^2 > 5.1\ (GeV/c)^2$. These will be the first measurements of the time-like proton form factors with muons.

In recent years, we have made experimental studies, employing a high temperature superconducting tube to shield the 1-2 T solenoid field in the interaction region of the PANDA detector. The publication summarizing the PhD thesis of Bertold Fröhlich has been finalized and recently been submitted to NIM A.

Construction of the backward endcap calorimeter

In 2021 substantial progress has been achieved in the construction of the backward endcap detector. All carbon fiber alveoles have finally been produced in 2021 with the necessary accurate tolerances in order to use them to mount the backward endcap. Each of the PWO-crystals is equipped with two large-scale avalanche APDs. The gluing of the 1400 APDs to the 700 PWO crystals has been started in 2021. About 5 % of the APDs are glued. All mechanical submodules for manufacturing the submodules as well as all temperature sensors are produced. The mounting plate which will be supported in the warm region and holding all crystal modules has been manufactured and is ready for setting up the backward endcap. 800 “APFEL” preamplifier ASIC chips have been delivered and soldered into a holding PCB connected to a flex-PCB and ready for building into the crystal modules. Concerning electronics, all necessary 40 ADC-boards with 64 channels per board from Uppsala University have been delivered and tested. In total we have 2560 ADC-channels ready. Additional electronics boards, like the sender-boards driving the signals from the APFEL preamplifier through long cables to the ADC are all available and tested. The high voltage distribution electronics is manufactured and ready to be used.

Preparation of a FAIR Phase-0 Experiment at the Mainz MAMI accelerator

A modified version of the PANDA backward endcap calorimeter will be used at the Mainz MAMI accelerator for a measurement of the pion transition form factor at a finite value of the four-momentum transfer via the Primakoff-process. This form factor is instrumental for hadronic quantum correction to the g-2 factor of the muon.

The simulations concerning the optimization of the setup have been further developed. As a result, we will employ an additional detector to separate electrons from high-energy gammas from pion decay, which will help to reduce combinatorial background and to improve the accuracy of the measurement. In addition, machine learning methods have been used to improve the position reconstruction for the high energy photons from pion decay.

A simulation concerning the radiation dose with crystal modules close to the beam line has been performed. In addition, a full study of the experimental acceptance has been performed as has been requested by the MAMI PAC as a reaction of the letter of intent.

As a necessary next intermediate step, a further beam test employing two prototypes of 16 PWO crystal modules each has been prepared for a beam test in 2022. The quartz glass fibers which serve for monitoring the stability of the detector via the injection of blue LED-light have been developed.

A GEM prototype detector has been setup and will be operated to test its suitability for the electron detector.

Section MAM: Matter-AntiMatter Asymmetry

Dmitry Budker

The MAM section is addressing fundamental questions in science related to the observed asymmetry of matter and antimatter in the universe, as well as the nature of dark matter and possible physics beyond the standard model. We also conduct applied research in the general field of quantum sensing.

During 2021, there have been numerous developments, the highlights of which we describe below.

The MAM Section is part of the CERN Physics Beyond Colliders study of the **Gamma Factory** – a proposed novel light source and a high-energy storage ring "ion trap" for fundamental physics (Fig. 5). We are spearheading the study of the physics reach of the facility. Several papers were published in a Special Issue of Annalen der Physik (co-guest-edited by Dmitry Budker), including a major review on "Expanding Nuclear Physics Horizons with the Gamma Factory" [D. Budker et al., Ann. Phys. (Berlin) 534, 2100284 (2022)].

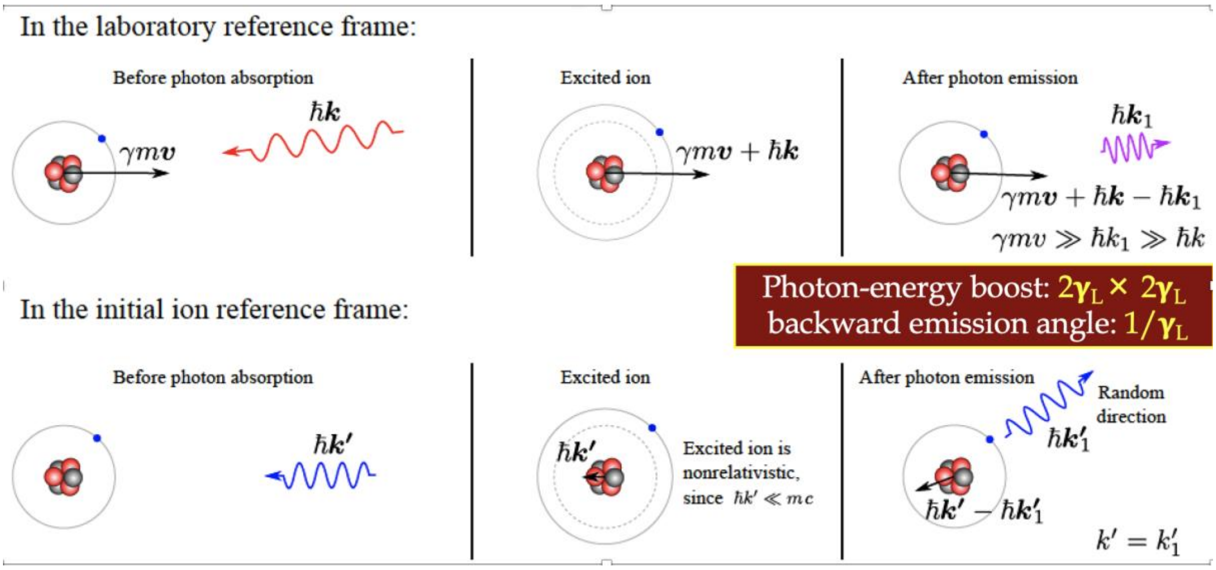

Fig. 5: The physical principle of the Gamma Factory: backward Compton scattering on an electron bound in an ultrarelativistic ion. © Alexey Petrenko, CERN

Laboratory searches for "new physics" remains a major research direction in MAM. Recently, we completed and published a search for new particles based on the nonlinearity of the so-called "King plot" that describes isotope shifts in different atomic transitions. The method was proposed by a collaboration including MAM scientists in 2018, and many experimental groups are working on this at the moment. We have also collaborated with several groups in China to search for possible "fifth forces" that may originate from beyond-the-standard model physics.

Cosmic Axion Spin-Precession Experiment (CASPEr) is our flagship project in the area of dark-matter searches. Significant progress has been made and two papers have been published discussing spectral signatures of axionlike dark matter [A. V. Gramolin et al., Phys. Rev. D 105, 035029 (2022)] and quantum sensitivity limits of nuclear-magnetic-resonance experiments searching for new fundamental physics [D. Aybas et al., Quantum Sci. Technol. 6, 034007 (2021)]. We are currently working with the "CASPEr-Gradient Low Field" apparatus, while, in parallel, designing the next stage of the project in anticipation of the arrival of the 14.1 T "high-field" magnet in the next few months.

Global Network of Optical Magnetometers for Exotic physics searches (GNOME) is world-wide collaboration spearheaded by MAM. It is perhaps the first network of a presently growing number, searching for “topological dark matter,” and a variety of other possible exotic-physics signals of astrophysical journals. The reporting period has seen several major results and publications. We are currently preparing the first science run using “Advanced GNOME” – a fully upgraded network with the next-generation atomic magnetometers and novel approaches to data analysis. Importantly, new search targets for GNOME are identified based on better understanding for dark-matter phenomena such as, for example, gravitational focusing of dark-matter streams and the physics of possible compact halos made up of ultralight bosonic fields.

Novel techniques to search for dark matter: Even though dark matter apparently constitutes 80 % or so of all matter in the Universe, its origin remains completely unknown. For this reason, it is important to devise new techniques that may be sensitive to a broad array of candidates. MAM has introduced a number of such techniques and presented the results during 2021. Examples include extension of the search for ultralight scalar dark matter in the radio-frequency range using atomic and molecular spectroscopy; search for “millicharged” dark matter using detection with ion traps; and the search for Axion Quark Nuggets (AQN) via infrasonic, acoustic and seismic waves produced by AQN during their passage through the Earth.

Laser Stars: As part of the atomic magnetometry research program, MAM has been involved in developing remote-sensing techniques using artificial stars using laser-excited sodium atoms in the mesosphere. During the reporting period, in addition to significant experimental progress in the laboratory, we helped introducing a new concept – that of photometric stars, which may become an important tool in the future studies of dark energy.

The work of the MAM Section on **Zero- to ultralow-field nuclear magnetic resonance (ZULF NMR)** has a broad range of applications from fundamental physics to chemistry to biomedical diagnostics and monitoring the efficacy of cancer therapies. It is the latter that has won an international interdisciplinary team spearheaded by MAM the 2021 Erwin Schrödinger Prize of the Stifterverband.

Section SHE: Superheavy Elements

Michael Block and Christoph E. Düllmann

In 2021, our section focused on the UNILAC beamtime within the FAIR Phase-0 program and on technical and methodological developments for studies of physical and chemical properties of actinides and transactinides. Representative aspects of the broad program are described in the following.

Several experiments focused on the nuclear structure. At TASCA, fission properties of Rf isotopes were studied employing the “FEBEX” modules developed at GSI. The population rates of the known fissioning isomeric states in ^{256}Rf with half-lives of ≈ 14 and ≈ 10 µs were determined to ≈ 18 and > 10%, respectively [J. Khuyagbaatar et al., Phys. Rev. C 103, 064303 (2021)]. As such rates are typical for two-quasiparticle high-K isomeric states in this region, this nature has been attributed to the present states. Ground-state spontaneous fission half-lives of light known Rf isotopes hint at a potentially abrupt decrease in half-lives of unknown neutron-deficient Rf isotopes with N <149, suggesting no further neutron-deficient Rf isotopes may exist. However, this conjecture was directly related to uncertainties in ^{253}Rf data. We revisited the ^{253}Rf decay and identified two fission activities. Based on our new data and in line with theoretical predictions, no abrupt decrease in the half-lives of the neutron-deficient No and Rf isotopes is expected. In addition, α decay, previously unknown, was observed in ^{253}Rf, leading to the discovery of ^{249}No [J. Khuyagbaatar et al., Phys. Rev. C 104, L031303 (2021). The discovery of ^{249}No was independently reported from experiments at FLNR Dubna [A. I. Svirikhin et al., Phys. Part. Nucl. Lett. 18, 445 (2021)].

The new Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal (ANSWERS) setup was invented in the SHE Chemistry department. It will provide improved detection and signal isolation capabilities to extract more detailed information on the decay of superheavy nuclei than is possible with current state-of-the-art setups. In 2021, in-beam commissioning of ANSWERS has been performed with ^{257}Rf. Many multi-coincidence events between α particle, conversion electron(s) and photons were observed. The data, currently under final analysis, represent a completely new type of data set, inaccessible with more traditional setups. ANSWERS holds great potential, e.g., for studies of fission of the heaviest nuclei.

The data analysis of the Fl decay chains registered in 2019 and 2020 in two runs at GSI was finalized. The experiment used an upgraded TASISpec decay station sensitive to α-electron and α-photon coincidences placed at the focal plane of TASCA. This allowed detailed nuclear spectroscopy of ^{286,288}Fl [A. Såmark-Roth et al., Phys. Rev. Lett. 126, 032503 (2021)] and ^{289}Fl decay chains. Thanks to the power of the used setup, a mere doubling of the ^{289}Fl world data set provides insight into the structure of the populated nuclei. Extensive nuclear structure calculations employing the symmetry-conserving configuration mixing theory support proper interpretation of the data, which provide valuable anchor points for theoretical predictions for the Island of Stability.

Mass spectrometry studies at SHIPTRAP focused on low-lying isomeric states that are so long-lived that their investigation by decay spectroscopy is difficult. The high mass resolving power up to 10^7 allowed for the first time to determine absolute excitation energies of these isomers accurately. A low-lying isomer in ^{241}Cf, expected to exist according to systematics in N=143 isotones and to predominantly de-excite via internal conversion with an estimated half-life of ≈ 0.2 ms was found, but must be more long-lived, exceeding the Weisskopf estimate by about three orders of magnitude. The excitation energy of ^{257m}Rf was accurately measured, and high-precision ground state masses of ^{257}Rf and ^{258}Db were directly determined at count rates down to 1 ion/day, extending our knowledge on the evolution of the N=152 shell closure towards heavier nuclides. In a parasitic experiment, the excitation energies of low-excited states in members of the α-decay chains ^{206}Fr-^{202}At-^{198}Bi and ^{204}Fr-^{200}At-^{196}Bi were determined.

Laser spectroscopy was performed on $^{249,254}Fm$ produced via the decay of $^{253,254}No$ as they are inaccessible directly. The isotope shift of the 25 112 cm^{-1} transition was precisely determined, concluding 2020 measurements. In addition, we improved the spectral resolution for the $^1S_1$-$^1P_0$ transition of ^{252}No previously studied. Technical developments focused on improving the RADRIS method. Employing fast HV switches minimized losses in short cycles, enabling future measurements of short-lived nuclides such as ^{251}No and improving the performance for the planned atomic level search in Lr. This will profit from improved predictions [E. V. Kahl et al., Phys. Ref. A 104, 052810 (2021)].

At HIM, a new gas-jet setup for high-resolution laser spectroscopy of heavy nuclei was commissioned. A thorough characterization of different nozzles shaping the supersonic jet was performed using images of fluorescence from optically excited stable atoms. Spectral resolutions down to 230 MHz were reached, corresponding to a Mach number of M=6.5. These studies pave the way for online studies of the $K=8^-$ isomer in ^{254}No.

Off-line laser spectroscopic measurements were performed at the RISIKO setup of Mainz University in collaboration with the group of Klaus Wendt. These became possible in 2021 using a remaining ^{254}Es sample that was delivered from ORNL to Mainz in 2019. This sample was post-irradiated at the high-flux reactor at ILL, Grenoble, France, to breed an increased amount of ^{255}Es ($T_{½}$=40 d), which β^--decays to ^{255}Fm ($T_{½}$=20 h). The irradiated sample was shipped back to Mainz just a few days after irradiation; four separations of ^{255}Fm, ingrowing from its mother ^{255}Es, were performed. Laser spectroscopy was carried out on different optical transitions in ^{255}Fm with sample sizes of (1-7) 10^6 atoms; also, the hyperfine structure of ^{255}Es was measured with improved spectral resolution.

Chemical studies of superheavy elements at TASCA focused on Nh and Mc, picking up on the successful 2020 TASCA beamtime. The produced 0.17-s ^{288}Mc was expected to be too short-lived for direct studies [A. Yakushev et al., Front. Chem. 9, 753738 (2021)] but decays into 1-s ^{284}Nh. Somewhat unexpectedly, several ^{288}Mc events were observed in 2020. In 2021, again ^{288}Mc was produced and was separated in TASCA, thermalized in a gas-filled recoil chamber, and transferred into the chromatography and detection setup. Eleven decay chains from ^{288}Mc and ^{284}Nh were registered, adding to the seven 2020 decay chains. The complete data set is under final evaluation and will provide first information on the interaction strength of Nh and Mc towards SiO_2. The preliminary analysis shows excellent agreement with theoretical predictions [V. Pershina et al., Inorg. Chem. 60, 9796-9804 (2021)].

For future studies of shorter-lived elements like Lv and Ts, a buffer gas stopping cell will be used for the thermalization of recoiling ions behind TASCA [S. Götz et al., Nucl. Instr. Meth. B 507, 27 (2021)], and the advanced “UniCell” is currently under construction.

To support interpretation of the experimental results on the reactivity of Fl obtained previously at TASCA, adsorption properties of atoms and oxides of Cn and Fl, as well as of the homologs Hg and Pb, on the Au(111) and on fully hydroxylated quartz surfaces were calculated using state-of-the art theoretical methods. The improved results confirm the earlier predicted sequence in the adsorption of the elemental atoms on gold: Pb >> Hg > Fl > Cn. On the hydroxylated α-quartz surface, the interactions of Hg, Pb, Cn and Fl were. Hg, Cn and Fl atoms should not interact with such a surface at room temperature, while Pb should adsorb.

Superheavy element production relies on optimized long-term stable targets of rare actinide isotopes. Improved methods are needed to produce targets in a thickness range up to > 1 mg/cm^2, able to withstand highest beam intensities as provided by ever more powerful accelerators. To this end, a two-prong approach is currently pursued. On the one hand, fundamentals of the most frequently used production technique, molecular plating (MP) are studied, and modern electrochemical production processes are evaluated in cooperation with the DECHEMA Research Institute, Frankfurt. On the other hand, microscopic and spectroscopic studies of heavy-ion beam-induced changes in f-element layers are performed together with the GSI Materials Research Department. Molecular-plated lanthanide targets, both unirradiated ones as well as targets that were previously irradiated with different fluences of ^{197}Au at the GSI M-Branch were analysed with various techniques. Ion-beam analysis was performed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), and elemental and structural modifications were studied with infrared spectroscopy (IR), Raman spectroscopy (Raman), X-ray photoelectron spectroscopy (XPS) and grazing incidence diffractometry (GIXD) at the JRC Karlsruhe in the frame of the RI Open Access scheme ActUsLab; the data are currently under final evaluation. In 2021, a new set of lanthanide targets was irradiated with ^{48}Ca ions at the TASCA beamline and is still in storage to allow decay of beam-induced radionuclides; they will be analysed in 2022.

A multitude of further targets and sources, mostly of actinides, was prepared in the SHE Chemistry section for studies, e.g., at TRIGA-TRAP and SHIPTRAP, as well as for use in collaborative work, including Am, Cm, Cf, Es, and Fm samples provided for laser spectroscopy studies at the RISIKO laser mass separator. The study of various aspects connected to the exotic low-energy ^{229m}Th isomer is performed in different collaborating groups. For such work, two ^{233}U recoil sources providing the α-decay daughter $^{229(m)}Th$ prepared by MP were shipped to KU Leuven, where $^{229(m)}Th^{+}$ will be extracted by a gas-jet to a laser ionization and spectroscopy setup. Metallic ^{232}Th laser ablation targets were shipped to the University of Granada, where Penning-trap based studies will be performed at the TRAPSENSOR facility, first with ^{232}Th and later with ^{229m}Th. Within the Laser Ionization and Spectroscopy of Actinides (LISA) MSCA-ITN, several ^{239}Pu recoil ion sources providing ^{235m}U, which is the second lowest-lying known nuclear isomer, were prepared by molecular plating. They will be used for hyperfine structure studies at University of Jyväskylä using the collinear laser spectroscopy technique, which provides high spectral resolution. For reference studies with the even-even neighbour ^{236}U, which shows no hyperfine structure, ^{240}Pu sources were prepared. A liquid source of ^{228}Ra placed in a container made from scintillating material was provided to the GSI nuclear spectroscopy department for use at the DESPEC setup. For this, 26.5 kBq ^{228}Ra were separated from about 10 g of ^{nat}Th. For fission studies at the LOHENGRIN mass spectrometer at ILL Grenoble, old targets containing 1 mg of ^{239}Pu were reprocessed. The JRC Geel, Belgium, aims on detailed investigations of undisturbed fission products from spontaneous fission sources like ^{248}Cm and ^{252}Cf, necessitating thin sources of spectroscopic quality placed on extremely thin backings like 10 µg/cm² C foils or 24 µg/cm² polyimide foils. The Drop-on-Demand (DoD) printing technique was employed. Parameter studies of the wetting behaviour of different solvents were performed to identify a system that provides thinner deposit layers on polyimide films than the standard water/acid-based system. Ethanol/water mixtures were found to provide superior layers as demonstrated with an ^{243}Am source and verified at JRC Geel. Eighteen large-area ^{241}Am calibration sources needed for the online calibration of a special detector array used in studies of neutron decays at the TRIGA Mainz and the ILL Grenoble were produced, also by DoD printing.

Section SPECF: Spectroscopy and Flavour

Achim Denig

The research section SPECF (SPECtroscopy and Flavour) is aiming for world class spectroscopy data of both hadrons and nuclei by a full exploration of the opportunities given by the future PANDA experiment at FAIR. Currently, during the construction phase of PANDA, the section has taken over the responsibility for the design and the construction of three sub detectors of PANDA:

- the PANDA luminosity detector (LUM),
- the hypernuclei und hyperatom setup for PANDA (HYP),
- the assembly of the bar boxes of the barrel Cerenkov detector of PANDA (DIRC).

As a preparation for the future physics program at PANDA, the research section is also involved in the BESIII experiment at the electron-positron collider BEPC-II in Beijing, where currently world-leading results in the field of hadron spectroscopy of light quark systems as well as charmonium(-like) hadrons are carried out.

Finally, within the context of the Helmholtz Excellence Initiative and in cooperation with the PRISMA+ Cluster of Excellence of JGU Mainz, a beam-dump experiment DarkMESA for the detection for Dark Matter particles at the future MESA accelerator is currently prepared.

PANDA Luminosity Detector LUM

The luminosity measurement at PANDA will be achieved by a dedicated tracking detector based on four layers of HV-MAPS detectors inside the vacuum of the HESR storage ring. The detector will measure the elastically scattered antiprotons of the proton target.

Within the context of a master thesis (Jannik Petersen, now PhD student), the survey and alignment of the vacuum box of the luminosity detector has been extensively studied. The deformation of the vacuum box was measured using a portable coordinate measuring device and the results were found to be in good agreement with FEM simulations. To allow for a precise luminosity measurement, the position of the pixel sensors inside the vacuum box needs to be linked to survey markers on the outside of the box with high precision. For this a portable measuring device has been used and was found to be functional as well.

During the spring of 2021, the last sample of electronic components, which are needed for the readout inside the vacuum box, were tested at COSY in Jülich. The parts were irradiated with protons with an energy of 2.8 GeV. After a dose of about 15 Gy, which is exceeding the expected dose during the lifetime of the luminosity detector, only one out of 45 components failed.

Finally, in detailed discussions with the contact persons for the HESR storage ring, the mechanical integration of the luminosity detector into the accelerator was discussed. The separation between the luminosity detector and the accelerator will be achieved by means of valves upstream and downstream of the detector.

Hypernuclear Physics Setup HYP

During the Phase 1 of PANDA, the $\bar{p}\ {}^{20}Ne \rightarrow \Lambda\Lambda$ interaction close to the threshold will be studied. The development of the reconstruction software has been continued. A major effort was the reconstruction of the very low-momentum decay products within the PANDA framework, which until now was only treated under so-called ideal conditions. It is also planned to study the $\bar{p}\,A \rightarrow \Lambda\Lambda + X$ and the $\bar{p}\,A \rightarrow \Lambda\Sigma^- + X$ reactions. In nuclear targets, these reactions probe the proton and neutron distributions, respectively, and may allow determining both the Σ^- potential but also the neutron variation of the skin thickness in different isotopes.

The design of the primary target station for the Ξ hyperatom measurement is finished and all parts are ordered. The passive positioning system for the target carriage has been improved. The assembly is somewhat delayed because of delivery problems of some components.

The construction of the PANGEA Ge array detector has continued at the GSI in cooperation with the DESPEC group. First parts for the holding structure for Ge detectors have been produced and are tested.

PANDA Barrel DIRC detector

A postdoc position for the DIRC glueing laboratory was advertised and successfully filled as of summer of 2021. Subsequently, work began on upgrading the laboratory for the glueing process of the bar boxes. Decisions on basic equipment were made and the optical tables were ordered. Designing of glueing fixtures has started. Furthermore, plans for environmental monitoring are being developed as this information is crucial for the glueing process. These activities are becoming more and more important as all ordered DIRC radiator bars have already been delivered to GSI and are being evaluated according to QA requirements.

BESIII analyses

The BESIII analysis of the direct production of the χ_{c1} resonance in electron-positron annihilation has been finalized and submitted to Phys. Rev. Lett. The measurement represents the first measurement of the production of a non-vector resonance in electron-positron annihilation with interesting perspectives for future measurements at high-luminosity colliders. The significance of the measurement is exceeding five standard deviations. The production of non-vector resonances in formation will be most relevant for PANDA, where corresponding energy scans will be possible with unprecedented statistics.

Section THFL: Theory Floor

Hartmut Wittig

Section THFL addresses a wide range of subjects in hadron and nuclear physics, using state-of-the-art theoretical tools such as QCD factorization, lattice QCD, perturbative QCD, and nuclear effective field theory. Activities are focussed on hadron structure, hadron spectroscopy, precision observables, nuclear effects in muonic atoms, and studies of the QCD phase diagram.

In **Hadron Phenomenology**, the group of Marc Vanderhaeghen extended earlier work on data-driven dispersive analyses of photon-photon fusion processes in the light quark sector to the reactions $\gamma\gamma \to D^+D^-$ and $\gamma\gamma \to D^0\bar{D}^0$ from threshold up to 4.0 GeV. The description is based on a partial-wave dispersive representation where the s-wave is solved using the N/D ansatz, with left-hand cuts accounted for using a model-independent conformal expansion, and the d-wave $\chi_{c2}(3930)$ state described as a Breit-Wigner resonance. The analytic continuation of the partial-wave amplitudes to the complex energy plane showed no evidence for a pole corresponding to the broad resonance $X(3860)$ reported by the Belle Collaboration. Instead, the data are consistent with a bound state below the $D\bar{D}$ threshold, with mass 3695(4) MeV, confirming previous phenomenological and lattice predictions. The existence of such a state $X(3695)$ may be tested in direct production at PANDA@FAIR.

Furthermore, nucleon-nucleon interactions were studied up to next-to-next-to-leading order using time-ordered perturbation theory in the framework of manifestly Lorentz-invariant chiral effective field theory. This framework has presented a two-pion exchange contribution at one-loop level, consistent with the corresponding non-relativistic expressions in the large-nucleon-mass limit. The phase shifts and mixing angles of the partial waves with the angular momentum $l \geq 2$ were calculated, and an improved description of the phase shifts for these higher waves, such as ${}^3D_3$ was found in comparison with the results of non-relativistic formulation.

A comprehensive review paper was published, which summarizes the situation concerning the proton charge radius in light of new experimental results from both atomic hydrogen spectroscopy and electron-scattering measurements, combined with state-of-the-art theoretical analyses.

In **low-energy precision physics**, the group of Jens Erler studied the two-loop electroweak corrections to polarized Møller scattering in two different schemes. Hadronic and perturbative QCD corrections to γZ mixing were incorporated through the weak mixing angle at low energies. The current theory uncertainty has been estimated to be about five times smaller than the anticipated uncertainty of the upcoming MOLLER experiment. Furthermore, the group has developed a method to compute the heavy quark contributions to the anomalous magnetic moment of the muon in perturbative QCD at three-loop order. The charm and bottom quark contributions could be determined, respectively, with an uncertainty of one and three orders below the anticipated final experimental uncertainty from the Muon $g-2$ experiment at Fermilab. The bottom and charm quark masses were the subject of another calculation based on pairs of QCD sum rules of moments of the vector current correlator in perturbative QCD at three-loop order. The approach is unique in that it is based on an over-constrained system, so that it is possible to derive calibrated uncertainties of 8 MeV in both cases. Furthermore, a strategy and an exploratory calculation has been presented for a first measurement of the parity-conserving axial-axial 4-fermion electron-quark couplings in deep inelastic scattering with the planned SoLID detector at Jefferson Lab.

Activities in **Lattice QCD** in the groups of Harvey Meyer and Hartmut Wittig focussed on calculations of the hadronic contributions to precision observables, structural properties of the nucleon, studies of hadron resonances and multi-baryon states, as well as investigations of the properties of the quark-gluon plasma.

The group has recently published results on the hadronic running of the electromagnetic coupling and the electroweak mixing angle. Both quantities are important for precision tests of the Standard Model. The relevant hadronic vacuum polarisation functions were computed for Euclidean momenta up to $Q^2 \leq 7\,\mathrm{GeV}^2$. When translated into an estimate of the hadronic running at the Z-pole, one finds agreement with results based on the traditional data-driven method, which have similar precision. At low Euclidean momentum transfers, however, a tension of up 3.5 standard deviations between lattice and phenomenological estimates was observed. Another milestone related to precision observables was the publication of the world's most precise evaluation of the hadronic light-by-light scattering contribution to the muon anomalous magnetic moment, using coordinate-space, by Meyer et al. The impact of the most precise lattice evaluation of the hadronic vacuum polarisation was reviewed for the general scientific public. An ancillary project in the context of precision observables concerned an improved determination of the lattice scale via the calculation of octet baryon masses including isospin-breaking effects.

Following last year's publication of the result for the proton radius, extracted from isovector electromagnetic form factors and experimental results for the neutron charge radius, the group has calculated the isoscalar electromagnetic form factors, including the contributions from quark-disconnected diagrams, thus allowing for the direct lattice determination of the proton and neutron charge radii and magnetic moments. In addition, the group has investigated the axial form factor of the nucleon, focussing on the accurate description of the dependence on the squared momentum transfer, which is required in future long-baseline neutrino experiments.

Lattice calculations focussing on hadron spectroscopy and hadronic interactions have extended the previously published determination of the binding energy of the *H* dibaryon to the case with SU(3)-flavour symmetry breaking and different spin states. In addition, calculations employing the Lüscher formalism were performed in the charm sector, focussing on the $X(2900)$, the $X(6900)$ and the charmonium-nucleon pentaquark state P_c. This activity is motivated by the recent discovery of a doubly charmed tetraquark T_{cc} below the DD^* threshold by the LHCb collaboration. THFL members have performed the first lattice QCD determination of the DD^* scattering amplitude required to theoretically establish this state, which is the longest-lived hadron discovered with manifestly exotic quark content $cc\bar{u}\bar{d}$. The result provides a clean signature for a pole in the corresponding scattering amplitude employing *ab initio* methods. This study opens an avenue for rigorous predictions of similar hadrons that await the discovery and improves our understanding of hadrons with more than three (anti)-quarks.

On the topic of quark-gluon plasma (QGP) properties with impact on heavy-ion collision phenomenology, the group of Meyer presented a lattice QCD analysis of the spatially transverse channel of electromagnetic current-current correlators, in order to extract the thermal photon emissivity of the QGP. This is the first such calculation performed with dynamical quarks. In addition, dispersion relations at fixed photon virtuality were used as a complementary method to study these correlators. This allows one to constrain the photon emissivity without confronting a numerically ill-posed inverse problem.

The **low-energy nuclear reaction** group led by Pierre Capel has extended their analyses of nuclear reactions involving halo nuclei using effective field theory techniques (Halo-EFT) to study knockout reactions. Even though a description of the halo nucleus at much higher energy than the breakup one is required, it could be shown that a Halo-EFT up to NLO was sufficient (and necessary) to properly describe experimental data. In the analysis of knockout reactions based on a common eikonal model, it was shown that the cross sections are strongly sensitive to the asymptotic normalisation constant of the initial bound state and that they are also affected by the presence of excited bound state in the projectile low-energy spectrum. Excellent agreement between experiments on ^{11}Be and ^{15}C and NLO descriptions of knockout reactions that also fit breakup, transfer and radiative-capture data has been observed. The only aspect of reactions involving halo nuclei that is not properly accounted for at NLO is the resonant breakup. To improve this, degrees of freedom of the core of the nucleus, viz. its excitation, should be accounted for, which can be achieved by introducing an *ad hoc* threebody force between the core of the nucleus, the halo neutron, and the target. Findings were summarized in a short review article. Furthermore, the group has continued the development of optical potentials to describe nucleus-nucleus interactions from first principles.

The ***ab initio* nuclear theory group** led by Sonia Bacca has focused on the calculation of charge radii in neutron-rich nuclei and on the study of electromagnetic response functions of medium-mass nuclei. Regarding the charge radii, a highlight was produced by the investigation of ^{8}He, a four neutron-halo nucleus. Bacca and collaborators have calculated the charge radius and the electric dipole polarizability using nucleon-nucleon and three-nucleon interactions from chiral effective field theory, both with and without explicit Delta degrees of freedom. By increasing the precision of coupled-cluster calculations via the inclusion of leading order three-particle three-hole excitations, it could be shown that the charge radius is consistent with the most recent experimental data, while providing a prediction for the polarizability, which serves as a benchmark for future experiments at rare isotopes facilities.
Regarding the study of electroweak response function, Bacca's group has computed, for the first time, the longitudinal response function for ^{40}Ca with *ab initio* methods, using chiral interactions with and without explicit Delta degrees of freedom. The main finding is that, both in the case of the delta-full and delta-less theory, final state interactions are essential for an accurate description of experimental data. This work presents a milestone towards *ab initio* computations of neutrino-nucleus cross sections relevant for experimental long-baseline neutrino programmes.

5. Helmholtz Excellence Network

Within the framework of the Helmholtz Excellence Network from the Initiative and Networking Fund (10/2017-03/2021), HIM extended its collaboration with the PRISMA+ Cluster of Excellence at Johannes Gutenberg-Universität Mainz, which started operation in January 2019. Many Principal Investigators of HIM are also PIs in the cluster PRISMA+. Three of them are members of the steering committee of the cluster.

Within the Excellence Network, the TACTICa project was pursued by the research sections MAM and SHE. Other projects concern precision measurements of the weak mixing angle via parity violating electron scattering (P2-experiment) and dark matter searches in beam dump experiments at accelerators (DarkMESA-project). These activities were supported by physicists from the SPECF and EMP sections as well as the Theory-floor section THFL.

Section EMP:
P2 – Precision Parity Violating Electron Scattering

In 2021, major steps towards the realization of the P2 experiment at MESA have been taken. The research and development work for the experimental setup has continued involving beam tests at the detector test beam area of the MAMI accelerator where prototype detectors for the integrating Cherenkov detector have been tested as well as prototypes for the luminosity monitor and electronics for the P2 spectrometer. The funds of the Excellence Network have been instrumental for hiring personnel for this research and development work. Based on these beam tests some of the research and development work could be finished and accordingly the central components of the P2 detector could be ordered. The large, 3 m bore solenoid magnet with a central field of 0,6 T is expected to be delivered in 2022. The optically polished high-purity quartz glass bars have been ordered and will be delivered up to June 2022. The photomultiplier tubes for the read out of the Cherenkov quartz glass radiators have been ordered and will be delivered in 2022. The Helmholtz Excellence Network funds have been important to perform and complete the research and development work. The P2 experiment is now entering the phase of setting up the experiment.

Sections MAM & SHE:
TACTICa – Trapping and Cooling oh Thorium Ions with Calcium

TACTICa is a collaboration of MAM (Dmitry Budker), SHE (Christoph Düllmann) and JGU QUANTUM (Ferdinand Schmidt-Kaler). In this project, we capture individual thorium ion in a Coulomb crystal of Ca^+ ions and then cool them and perform precision quantum-logic measurements for fundamental-physics tests.

TACTICa focuses on laser-based research on ^{229m}Th with the aim of gaining new insights in fundamental physics. Current emphasis is on commissioning a newly built dedicated optimized Paul trap, on the development of methods to tag stochastically emitted ^{229}Th ions entering a ^{40}Ca ion crystal, and on the efficient cooling of trapped Th ions to energies lower than are achievable by Doppler-cooling.

Section SPECF:
LOWDASA – Low-mass Particles of the Dark Sector at Accelerators

Within the Helmholtz Excellence Network, SPECF is also engaged in the development of a beam-dump experiment at MESA (DarkMESA), which will search for sub-GeV dark matter (DM) and which will be performed behind the beam dump of the MESA external electron beam.

Various dark-sector models motivate the existence of sub-GeV DM, accessible in this type of beam-dump experiment, e. g. by coupling to a dark photon mediator A'. In the presence of light DM in the dark sector with masses $2m_\chi < m_{A'}$, the A' would predominantly decay invisibly into χ particles. The experiment exploits the MESA high-intensity electron beam and will run parasitically to the scheduled program of the P2 apparatus. The experiment is based on a solid and reliable detection technology and will collect an unprecedented accumulated charge in a few years' time, extending current limits on light DM (LDM).

A dedicated calorimeter design has been developed within the Excellence Network. Recently, also a study how to suppress cosmic ray background for DarkMESA has been finalized. A prototype detector consisting of PbF_2 crystals, and a cosmic ray veto shielding has been essentially finalized and is ready for extended test runs. For the second stage of the experiment, a large setup of existing lead glass blocks and PbF_2 crystals will be used. For the third stage, several innovative detector technologies are currently evaluated.

6. Externally Funded Research Groups

End of 2020, HIM comprised three externally funded research groups. Mustapha Laatiaoui and Dionysios Antypas hold ERC starting and consolidator grants, respectively. Danila Barskiy has won the Sofja Kovalevskaja Award from the Alexander von Humboldt Foundation which also entitles him to form a research group. These research groups are associated to the MAM section (Barskiy, Antypas) and the SHE section (Laatiaoui). The MAM groups have been established during the second half of 2020, Laatiaoui's group started in July 2019. We give a short summary of the activities in the research groups.

Parity Violation in Ytterbium

Dionysios Antypas (ERC Starting Grant)

We carried out preparatory steps and completed apparatus upgrades towards improved measurements of atomic parity violation. In addition, we carried out the following activities:

- Isotope-shift spectroscopy of neutral ytterbium in search of beyond-standard-model bosons [N. L. Figueroa et al., Phys. Rev. Lett. 128, 073001 (2022)]. This activity helped evaluate and eventually rule out the hint for a possible new-physics signal that was announced in 2020.
- Experimental search for ultralight dark matter through an improved check for fundamental constant variations with spectroscopy of atomic cesium [O. Tretiak et al., arXiv:2201.02042].
- Final stage of an experimental search for ultralight dark matter through a check for fundamental constant variations with spectroscopy of molecular iodine [R. Oswald et al., arXiv:2111.06883 [hep-ph]].
- An experiment was conceived and initiated in my group, involving frequency comparison of a solid-state oscillator with a hyperfine atomic clock, to sensitively explore fundamental constant variations.

Relayed hyperpolarization for zero-field NMR

Danila Barskiy (Sofja Kovalevskaja Award)

Our group demonstrated for the first time that the parahydrogen (pH_2) based SABRE-relay method (SABRE = Signal Amplification by Reversible Exchange) can be used as general means of generating hyperpolarized signals for zero- to ultralow-field (ZULF) nuclear magnetic resonance (NMR). This method is applicable to a wide range of small molecules possessing exchangeable protons such as alcohols, amines, sugars, and phosphates. We also explore the magnetic-field dependence of the proton hyperpolarization efficiency in SABRE-relay, and show the existence of a second, previously unexplored maximum at 19.0 ± 0.3 mT [E. Van Dyke et al., 10.26434/chemrxiv-2022-1njs9]. We explain the observed phenomenon and demonstrate that water does not significantly diminish SABRE-relay performance using benzylamine as polarization-transfer agent. Applications of the proposed approach in combination with ZULF NMR include detecting chemical impurities and measuring *J*-spectra from natural extracts. Further studies to investigate possibility of polarizing components of biological fluids such as urine, plasma, serum, are underway with measurements by portable and light-weight ZULF NMR spectroscopic tools.

Atomic Physics via Ion-Mobility Studies

Mustapha Laatiaoui (ERC Consolidator Grant)

A novel method to study the atomic structure of heavy and superheavy elements has been recently proposed under the name of Laser Resonance Chromatography (LRC) [M. Laatiaoui et al., Phys. Rev. Lett. 125, 023002 (2020)]. This technique is designed to enable laser spectroscopy on lawrencium and beyond. It uses laser excitations to change the ratio of ions in excited metastable states to those in the ground state by optical resonance pumping. Because of different transport properties for different states in dilute gases, they move at different velocities through a drift tube to a detector, enabling state-specific ion separation and resonance detection.

The LRC setup is meanwhile almost complete, and the commissioning phase has begun with the verification of the functionality of key components and the FPGA-based data acquisition system. After this phase, testing of the cryogenic drift tube will initially begin with ion mobility measurements on laser-ablated Cu^{+} ions.

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