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Progress Report 2023 – Scientific Annex

Program “Matter and the Universe”

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Program "Matter and the Universe" (MU)

Along with the Program Progress Report 2023, the program MU presents some scientific insights in its activities in 2023.

1 Introduction

The MU program is characterized by a particular breadth and depth of expertise in its coherent approach to advancing the understanding in elementary particle physics, astroparticle physics, and the physics of hadrons and nuclei. The joint research is carried out by experimental and theoretical methods, by modeling and observations, by technological developments, and by operating of and measurements on large research infrastructures. The research in MU is particularly characterized by international cooperation of different research institutions, which are organized in (partly very large) collaborations. This work is made possible by globally unique research infrastructures at our Helmholtz centers and at other international research centers and facilities. The program performs the research within three topics and two LK-II research infrastructures:

Program topic 1 - Fundamental Particles and Forces - investigates the most fundamental building blocks of the world and their interactions, addressing fundamental questions of nature, such as the origin of mass, the structure of the vacuum, the imbalance between matter and antimatter in the universe, or the nature of dark matter. The scientific highlight in 2023 was the publication of a slew of important results of the Belle II experiment with the luminosity of more than 400 fb^{-1} accumulated before its first long shutdown, addressing both precision measurements of standard model parameters and extremely rare decays with the aim of identifying non-standard process that address some of the challenges of the topic. Among the results are the world's most precise single measurement of the tau lepton mass, lepton flavour universality violation measurements in the tau sector, a study of the decay of tau leptons into three muons leading to the world's most precise limit on this decay, and the measurement of the decay $B^+ \rightarrow K^+ \nu\bar{\nu}$ that offers high sensitivity physics beyond the standard model. Of vital importance for the next physics run will be the newly installed second pixel-vertex detector PXD2 that was assembled and commissioned at DESY in 2022/23.

Program topic 2 - Cosmic Matter in the Laboratory - explores the formation of matter from the elementary building blocks and the various aspects and role of the strong interaction in these processes. Extreme forms of matter are created in the laboratory to recreate the formation of primordial matter and to understand extreme astrophysical objects such as neutron stars. The highlight of this topic in 2023 was achieved by ALICE experiment at the LHC by an international research team with leading participation of CML scientists. Scientists from GSI measured for the first time at the LHC in proton-proton collisions the charm fragmentation fractions, $f(c \rightarrow H_c)$, which represent the probability for a charm quark to hadronize into a given charm hadron. Charm quarks were found to form baryons almost 40% of the time, which is four times more often than what was expected from previous measurements at colliders with electron beams. These measurements demonstrate that the process of colour-charge confinement and hadron formation is still a poorly understood aspect of the strong interaction. Future measurements providing much more precise data during the next runs of the LHC will allow these questions to be scrutinised in much more detail and, correspondingly, to further expand our knowledge of the strong interaction.

Program topic 3 - Matter and Radiation from the Universe - has the largest structures of the universe and the properties of the fundamental building blocks as its research topic. Astroparticle physics in MU is carried out at observatories at extreme locations on Earth and at high-precision experiments in laboratories. The highlight of this topic in 2023 was the proof of the existence of high-energy neutrinos from the Milky Way by the IceCube collaboration in which both Helmholtz centers DESY and KIT are active. The IceCube Neutrino Observatory has now succeeded for the first time in creating an image of the Milky Way with neutrinos. Neutrinos are traces of the high-energy cosmic radiation that is generated and accelerated in the Milky Way. IceCube searched for neutrino emissions using machine learning techniques developed within the German IceCube network and applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models with a background-only hypothesis, the identification of neutrino emissions from the Galactic plane at a significance level of 4.5σ was possible. The signal is consistent with the diffuse emission of neutrinos from the Milky Way, but could also originate from a population of unresolved point sources.

LK-II Research Infrastructure – GridKa – as a WLCG Tier-1 center, is responsible for the processing, reprocessing, and archival storage of raw data from the LHC and future HL-LHC experiments as well as from specific MU astroparticle physics observatories. Other WLCG centers, in particular Tier-2 centers, rely on GridKa as their data source and data archive. In 2023, compute and storage resources were provided along the requirements of the experiments. The GridKa batch farm was upgraded in terms of security software and because of the higher energy costs, more energy-consuming compute nodes were switched off, without affecting the pledges of GridKa resources to the international user community. The development of the COBalD/TARDIS software for opportunistic computing was successfully continued.

LK-II Research Infrastructure – GSI-MU Ion Facilities – are operating large and worldwide unique heavy-ion accelerators, which serve a multitude of scientific topics. It also includes the GSI Green IT Cube, the main facility for all computing activities on the campus. In 2023, due to rising costs for energy and materials in addition to extended construction works in the building of the UNILAC accelerator, no beam time for scientific experiments on MU topics have been offered. Instead of user operation an extended engineering run for accelerator tests and optimization. The user beam time will start in February 2024. All experiments rated with "A" by the Program Advisory Committees in 2022 could be scheduled during those beam times in 2024 and 2025. At the Green IT Cube of GSI, the establishment of the AI innovation laboratory "GSI/FAIR Digital Open Labs was completed. The Digital Open Lab is now one of the flagship projects of intensive development cooperation between industry and academia.

2 Topic 1 – Fundamental Particles and Forces

Participating Centers: DESY, KIT

Topic 1 is structured into three subtopics: i) Higgs properties and fundamental interactions at high precision; ii) Searches for new particles and phenomena; iii) Cosmology and the dark sector of the universe. Significant work is also spent on technological aspects like detector and accelerator R&D, system integration, or scientific computing, software etc. Here, we will treat specific aspects of these efforts that are not part of the "Matter and Technologies" program under the heading of "Detector R&D and construction, accelerator R&D, system integration, computing".

A major milestone was reached with the installation of the new Belle II pixel-vertex detector PXD2 into the Belle II experiment. The detector is essential for vertexing, especially at the higher luminosities expected after the ongoing long shutdown 1.

ALPS II data taking started in May 2023, with a first ramp of the magnets to nominal current. This is a major achievement after a 20 year long preparatory phase, and it marks the beginning of an era of axion and dark matter search experiments on the DESY campus.

The electronics design of the active read-out elements for the CMS high-granularity calorimeter HGCAL has been transferred to the various geometries needed for the endcap detector, and prototypes for all sizes have been successfully tested.

In November 2023, the WPC Symposium took place, and with it the award ceremony for the Hamburg Prize for Theoretical Physics 2023, which was awarded to Edward Witten from the Institute for Advanced Study, Princeton, for his contributions to the shaping of our understanding of space, time, and the structure of the cosmos. Witten's research connects well with activities carried out by many colleagues in Hamburg, and he will spend a significant time at DESY in 2024.

The topic has delivered numerous results in spite of several significant challenges, not least a necessary reduction in the numbers of Ph.D. students and postdocs. On the personnel side, Johannes Braathen has just started a new Emmy Noether research group that in the theory group, working on Higgs and BSM physics. DESY Atlas member Priscilla Pani has been awarded an ERC starting grant.

In early summer 2023, the **LHC** ran very well, even producing a record for the luminosity integrated within 24 hours of 1.2 fb^{-1}. However, a vacuum leak occurred in early July. This damage could be repaired quickly, but a total of six weeks of data collection was lost. Subsequently, the LHC recorded lead-lead collisions until the end of the 2023 run. The plan for 2024 – 33 weeks of data taking – has not changed and also reflects CERN's efforts to save financial resources. After the implementation of many improvements to the accelerator and the Belle II experiment, the first Long Shutdown (LS1) of **SuperKEKB** is coming to an end. The pre-accelerators resumed operation in late 2023, and the **Belle II** physics run is expected to start at the end of January 2024.

Significant progress was achieved for the **DESY on-site experiments**: **ALPS II** has started its initial science run at the end of May 2023. Although in its current setup the experiment is primarily targeting the understanding of stray-light background, ALPS II is expected to improve the sensitivity on the axion-photon coupling strength by two orders of magnitude compared to predecessors already in early 2024. For **BabyIAXO,** a detector prototype has demonstrated the required extremely low background rates, a prototype of the custom-made X-ray optics has been qualified, the vacuum and gas system has been reviewed very positively, the magnet design is close to be finished, and new opportunities for the superconducting magnet cable (previously a Russian contribution to BabyIAXO) have shown up. DESY and the collaboration partners acquired significant new third-party funds for the construction of BabyIAXO, with the ERC Synergy Grant "Dark Quantum" lead by Igor G. Irastorza (spokesperson of BabyIAXO), which will extend the physics case of BabyIAXO. Another leading scientist from KIT in the Research Field Information also participates in this project. **MADMAX** has seen first data taking during 2023 with various prototype systems using the CERN MORPURGO magnet - a support for which the collaboration is highly grateful.

The **LUXE Collaboration** has recently published its TDR [1] and the collaboration has grown to over 100 members from 20 institutions. For funding reasons and due to a focus on the highest DESY priority – PETRA IV – the next steps in the realisation of the experiment (e.g. the construction of the extraction beamline) are currently uncertain and need to be clarified in the upcoming months.

The theoretical physics activities in the topic often touch upon more than one of the FPF subtopics introduced above. With more than 100 theory publications in 2023, we can here only concentrate on a few highlights. A postdoctoral fellow (A. Mitridate) in the theory group played a vital role in one of this year scientific highlights, namely a result from the NANOGrav Collaboration reporting convincing evidence for the presence of a gravitation wave background permeating our galaxy. The collaboration published a measurement that shows evidence for low-frequency (years-decades) GW using a 15-year data set of pulsar data collected e.g. with the Very Large Array in New Mexico. A. Mitridate studied possible sources for this signal, e.g. a population of supermassive black-hole binaries residing at the centre of most massive galaxies [2], but also other (more exotic) explanations [3]. Future data will be needed to distinguish between such explanations. Another highlight was that in string theory new techniques to comprehend the behavior of strongly interacting systems that feature resemblance with what is expected in a consistent description of gravity at the quantum level were developed [4]. And the role of new types of symmetry associated to non-trivial topology of extended objects to understand quantum effects like anomalies has been explored [5].

The question of **future international collider projects** continues to be debated vigorously. Old and new ideas for future machines are being brought up and are actively discussed, not least during the recently concluded US Snowmass and P5 processes with strong DESY contribution[1], or in the European, national and division-wide discussions on future facilities. A new concept called HALHF, developed by DESY scientists [6], is discussed in the report of the program *Matter and Technologies*. Scientists in the FPF topic are represented in various bodies relevant for developing the future of the field

[1] https://www.usparticlephysics.org/2023-p5-report/

(ICFA, ECFA, LDG, KET in Germany, etc.). As an example of the work that is also carried out in close collaboration between experimentalists and theorists, particle phenomenologists scrutinised the physics potential of a future Higgs factory in anticipation of the next European Strategy Update [7].

Related to the subtopic "**Higgs properties and fundamental interactions at high precision**", both ATLAS and CMS produced numerous measurements. The experiments have e.g. measured the top-antitop quark cross section with Run 3 data at 13.6 TeV [8, 9] with substantial DESY contributions. DESY scientists also contributed strongly to the CMS publication on the evidence for four-top production [10] at 13 TeV. The first evidence a rare SM process was also announced, in which a top quark is produced in association with a W boson and a radiated Z boson [11], and ATLAS for the first time observed a rare process where a W, Z, and a high-momentum photon were produced [12]. New results have also been obtained in the Higgs sector: CMS has performed measurements of the Higgs boson with its subsequent decay to two bottom quarks in different production channels: in vector boson fusion [13] and in association with one or two top quarks [14]. Combining several decay channels, ATLAS has measured the Higgs boson mass with unprecedented precision, where the single measurement with highest precision has been performed with strong contribution from the DESY group in the diphoton [15]. The experimental Higgs activities in the topic are accompanied by theoretical and phenomenological studies, see e.g. [16]. Furthermore, ATLAS has measured the coupling strength of the strong force with record precision [17].

Belle II has recently published the world's most precise single measurement of the tau-lepton mass carried out by DESY members [18]. Precision measurements of fundamental parameters allow sensitive tests of the standard model (SM) of particle physics. The new result is in agreement with previous determinations.

Theoretical effort by KIT theorists in cooperation with other theory groups led to the derivation of an analytical formula for the subtraction of infrared divergences at next-to-next-to-leading order (NNLO) for any collider process with massless final states [19], which is an important ingredient for predictions matching the precision of the LHC experiments.

The second subtopic "**Searches for new particles and phenomena**" is motivated by the various shortcomings of the SM. Members of ATLAS and CMS have contributed to numerous phenomenology studies, both for standard model physics and beyond [20-22]. ATLAS combined results from a wide range of searches to constrain a Two-Higgs-Doublet Model [23]. CMS members have performed a phenomenological study on the production of long-lived axions [24], which will now be transformed into a full CMS analysis. CMS has published, with large DESY participation, two searches for supersymmetry [25,26].

Already in 2021, Belle II published a first search for the rare decay $B^+ \rightarrow K^+\nu\bar{\nu}$ with only 63 fb^{-1} of data [27]. Due to its small SM branching fraction of about 6×10^{-5}, this channel offers high sensitivity to BSM physics. In a new analysis with a considerably larger data set, the sensitivity could be significantly improved thanks to a new inclusive selection that has been developed at DESY. Using the full pre-LS1 data, the updated analysis reports the first evidence for this decay with a significance of 3.5 standard deviations above the null hypothesis [28]. As the result is 2.8 standard deviations higher than the SM prediction it has already sparked considerable interest in the theoretical community.

Different scenarios with particles that feebly interact with standard model particles have been investigated and those could soon be tested at upcoming facilities like FASER suited for the detection of neutrinos and long-lived particles [29]. Possible signatures of non-standard Higgs bosons at the LHC have been investigated in several papers with major KIT contributions. A highlight of these is the search strategy to confirm or rule out the charged-Higgs explanation of anomalous flavor-physics data [30].

Recent results in the subtopic "**Cosmology and the dark sector of the universe**" cover e.g. the search for long-lived particles at Belle II [31] or a search for dark matter with ATLAS [32].

In a collaborative effort, DESY/UHH and Fermilab launched an R&D program based on the former MAGO collaboration (led by INFN Genoa) to search for high-frequency gravitational waves (GW) and axions using super-conducting radio-frequency cavities. Since July 2023, the MAGO cavity is at DESY for measurements and matching simulations to characterize the cavity before surface treatment and cold measurements at Fermilab. Previous theory calculations were improved to take into account sub-leading effects [33]. The aim is to use this cavity for a first GW search at Fermilab and to develop new cavities and a dedicated readout, cryostat and suspension system for future improved GW measurements hosted in the DESY cryo-platform. Also in the context of gravitational waves, the result of the NANOGrav Collaboration was already reported upon above [2]. This result has stirred significant further interest, triggering for example discussions in the theory community whether NANOGrav has observed dark sector phase transitions [34].

A lepton-flavored Dark Matter model was studied in [35] and a connection between dark matter and LHC physics was worked out in [36] from KIT scientists.

A significant part of the detector effort in the FPF subtopic **“Detector R&D and construction, accelerator R&D, system integration, scientific computing”** is the construction of two end-caps for the upgraded ATLAS and CMS silicon trackers. The required infrastructure is in place, and the production of parts is ramping up. Both ATLAS and CMS face supply-line problems for some components of the production. Both projects are, however, still on track for timely delivery to CERN in 2027, according to the current HL-LHC schedule. For CMS, the first PS kick-off module has been built at DESY, and its noise performance has been found to be unchanged with respect to earlier prototype modules. Furthermore, the DESY CMS group has successfully performed a so-called “Dee integration” exercise together with groups from Aachen, KIT, Louvain, Lyon and Bari, where seven 2S and six PS modules have been mounted on a prototype “Dee” structure and operated in parallel. The ATLAS end-cap is also taking shape. Various mechanical parts as well as the interface electronics are in production at DESY. All quality control tests for the module production are finalized. The biggest recent milestone is that a fully equipped petal produced at DESY with 18 production-grade modules was inserted in the system test and successfully operated at the operation temperature of -30°C. For the CMS high-granularity calorimeter HGCAL, the endcap geometry requires the design of active elements to be realized in a variety of shapes and sizes, and the basic types from the smallest to the largest have now been successfully prototyped and serve as a basis for a pre-series production. High granularity also challenges computing; low-level energy calibration procedures have been implemented with GPU and CPU support, where GPUs were shown to provide significant speed-up in realistic scenarios.

For the LUXE experiment, the technical design report could recently be published [1]. Meanwhile, progress on many fronts of the LUXE experimental setup has been achieved: Significant steps have been taken for the track pattern recognition with quantum computing techniques. A publication has been submitted to the journal [37], and the techniques are now also being applied to tracking for collider experiments (at e.g. a future muon collider). Various prototypes of subdetectors have successfully been operated and tested. There is also ongoing detector optimization work for the LUXE-NPOD approach – i.e. the dark matter / ALP search extension of the experiment.

Concerning LHC computing, the HPC group at KIT has extended the distributed computing infrastructure of CMS [38]. Furthermore, novel IT technologies are being researched with regard to the evolution of computing models for the High Luminosity LHC as well as evaluating their applicability to other research areas. In particular, focusing on increasing the efficient and sustainable utilization of computing resource and the performance of data analyses are aims of the KIT activities.

In 2023, KIT developed a dynamic and distributed grid computing and analysis infrastructure for the DARWIN experiment based on previous developments made for the PUNCH4NFDI computing infrastructure [39] and transitioned it into prototype operation using the Compute Resource Manager COBalD/TARDIS developed at KIT as its key component.

As part of the joint research project FIDIUM, further developments of COBalD/TARDIS enabled us to integrated wind-powered (CO2-neutral) compute resources from Lancium Computing Inc. (Texas, USA) into GridKa and thus making them available to WLCG for the first time. Furthermore, a simulation for distributed computing infrastructures has been developed in 2023, allowing for planning the future HEP computing infrastructure and enabling us to evaluate a large variety of possible designs of such a modernized infrastructure.

Software constitutes a backbone for the development of future experiments. The key4HEP software stack, developed and supported with leading contributions from DESY, is used in essentially all Higgs factory studies and presently bearing fruit in the advances made by FCC detectors towards full simulation models. Machine learning techniques hold the promise to effectively address future computing challenges brought about by higher luminosities as well as higher detector granularities, for example by using generative networks for fast shower simulation [40, 41]. Having started from idealised configurations, now, step by step, more realistic situations are successfully addressed, with arbitrary angles of particle incidence or with techniques independent of specific detector geometries.

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3 Topic 2 – Cosmic Matter in the Laboratory

Participating Center: GSI

Topic 2 is structured into four subtopics: i) hadrons properties and their excitation spectrum; ii) QCD phase structure and microscopic properties of QCD matter; iii) nuclear structure, nuclear reactions, and superheavy elements and their relevance for nuclear astrophysics: iv) matter–antimatter asymmetry and tests of fundamental symmetries. Significant work is devoted to technological aspects like detector R&D, system integration, software developments etc. in cooperation with the program MT. Theoretical calculations are indispensable to gain insights from measurements. CML theory groups work closely together with their experimental colleagues. In 2023, the CML completed successfully various milestones and achieved impactful physics results for all subtopics.

Understanding the properties of hadrons and their excitation spectrum: The production mechanisms and spectroscopy of baryons with strangeness contents, i.e., hyperons, were put in focus by HADES. Activities in 2023 were dedicated to the analysis of pp scattering data taken in 2022 and new kinematic fitting libraries have been successfully implemented [1]. Various physics channels are presently being studied involving novel machine-learning algorithms for particle identification including determination of time-integrated luminosity [2]. The $pp \rightarrow \Xi^- K^+ K^+ p$ reaction channel has been studied in detail. In addition, the pion beam offers a unique opportunity to study baryonic resonances generated at a fixed center of mass energy [3-5]. These studies are particularly important to verify ρ meson behavior in hot and dense QCD matter.

Proton beams from SIS100 with center-of-mass energies up to $\sqrt{s}$ = 7.5 GeV will enable a hadron physics program with CBM at FAIR. Promising opportunities in the field of spectroscopy and structure with hyperons with strangeness |S|=2,3 and in the domain of near-threshold hidden- and open-charm production were identified. The near-threshold production of J/ψ in pp collisions is of particular interest.

For PANDA, a new algorithm called the Apollonius-Triplet-Track Finder was developed focusing especially on secondary vertex tracks and allowed to improve the reconstruction efficiency by more than a factor 4. The KOALA experiment, for measurement of the differential cross section of $\bar{p}p$ elastic scattering for PANDA, has been commissioned at COSY by measuring the pp elastic scattering. In addition, CML scientists prepare a measurement involving the backward end-cap calorimeter of the PANDA in the framework of the FAIR Phase-0. It will be used to measure the pion transition form factor at the MAMI accelerator facility in Mainz, the leading contribution to the hadronic light-by light correction to the muon anomalous moment. For the three further subdetectors of PANDA at FAIR, namely the luminosity detector, the hypernuclear physics setup and the DIRC detector, major progress has been achieved. CML scientists are also involved in hadron spectroscopy and in hadron structure analysis of BESIII data at the tau-charm factory BEPC-II, e.g. launching a program of analyses of radiative J/ψ decays at BESIII.

CML theory have produced several research highlights in the area of nucleon form factors and matrix elements employing lattice QCD calculations. Results from a precision lattice calculation of the pion-nucleon sigma-term with a total error of 8% were published, which is in slight tension with the result determined from pion-nucleon scattering [6]. The first complete calculation of the electric and magnetic radii of proton and neutron was performed, including the previously neglected contributions from quark-disconnected diagrams and presenting a full error budget [7, 8]. These results favor the small electric charge radius. The same calculation has produced the first lattice calculation of the proton's Zemach radius [9] which is a crucial input quantity for measuring the hyperfine splitting in muonic atoms.

Establishing the QCD phase structure and understanding the microscopic properties of QCD matter at vanishing and high net baryon densities: After the successful ALICE operation in LHC Run 1 and Run 2 (for a compendium of results see [10]), the experiment was upgraded to cope with the increased LHC luminosity planned in Run 3 (2022-2025). In 2023, the LHC delivered 13.6 TeV pp collisions and 5.36 TeV Pb-Pb collisions. The number of events collected in Run 3 exceeds by two orders of magnitude the total pp statistics from Runs 1 and 2. The measurements of heavy flavors and composite particles are particularly profiting from the increased sample. In Pb-Pb runs, ALICE recorded collisions up to 47 kHz, the maximum interaction rate offered by the LHC. This is 40 times more than the total minimum-bias sample from Run 1 and 2. The yields of particles and antiparticles at mid-rapidity agree within 1%. This finding with its discussion in terms of the chemical potential are given in [11]. The measurement of the interaction of antihelium-3 with ALICE detector material [12] allowed to estimate the absorption of this particle in the universe and thus to interpret the antihelium-3 measurements done by AMS. The world's most precise measurement of hypertriton's ${}^{3}_{\Lambda}\mathrm{H}$ lifetime and its Λ separation energy is achieved by ALICE [13]. Like nucleons coalesce into nuclei, independently created charm and anticharm (c and cbar) quarks can coalesce into a J/ψ meson. This production mechanism, predicted more than two decades ago, is clearly visible in the recent high-statistics measurement by ALICE [14-16].

The 2023 activities were largely focused on the conversion of the HADES spectrometer into the configuration for experiments with heavy ions scheduled for Feb-Mar 2024, analysis of heavy-ion data collected in 2019 and a campaign to find measures for reducing uncertainties in the comparison of inclusive hadron spectrum data with respective calculation using microscopic transport calculations. High precision measurements of flow coefficients up to order of n=4 for protons, deuterons and tritons relative to the first-order spectator plane have been performed in Au+Au collisions [17]. The analysis of 15 billion Ag+Ag events progressed substantially and results for publications have been produced for the multi-differential dielectron continuum, weak decays, light meson and light nuclei production and azimuthal anisotropy. CBM detector technology, the free-streaming DAQ and data transport system and packages of the CBM online/offline software are being extensively tested and further optimized under realistic experiment conditions employing mCBM set-up. In 2023, focus was on understanding the detector performance in high-rate environment collected in 2022 and preparation to the high-rate run in 2024 to demonstrate the capability of online reconstruction of Λ hyperons. It could also be demonstrated that the CBM experiment with its design goal of a peak rate capability of fully analyzed 10^7 interactions per second is worldwide unique.

The most important signature for the passage of matter through the critical endpoint is a change in correlation length and associated different fluctuations of conserved charges. In [18] it was shown that the suggested mapping between protons and net baryons only works for small volumes, while for larger volumes non-trivial dynamic scatterings play a role. Furthermore, the fate of fluctuations in the hadronic rescattering phase has been investigated in [19]. The understanding of the mechanisms for the production of weakly bound clusters, such as a deuteron, in heavy-ion reactions at mid-rapidity is presently one of the challenging problems which is also known as the "ice in a fire" puzzle. It has been found that the quantum nature of the deuteron in coordinate and momentum space reduces substantially the kinetic deuteron production in a dense medium as encountered in heavy-ion collisions. Adding the "potential" deuterons by applying an advanced minimum spanning tree procedure, it was possible to obtain a good agreement with the available experimental data from SIS energies up to the top RHIC energy [20]. It is demonstrated that the presence of a phase transition in heavy ion collisions, at beam energies that probe dense QCD matter, leads to a significant enhancement of the dilepton yield per produced pion due to the extended emission time [21]. Review articles that summarize the main findings and open questions in the field of heavy-ion physics were published with CML scientist as main authors [22-24].

Understanding nuclear structure, nuclear reactions, and superheavy elements as well as their relevance for nuclear astrophysics: In 2023, the origin of the effects of the ^{208}Pb shell closure was studied and revealed that the sequential fission process could be responsible for the origin of the heavy fragments around ^{208}Pb. The technical developments and results on probing the opportunities and limitations of in-gas-cell laser spectroscopy of the heaviest elements with RADRIS were published in [25]. The collaboration with JGU Mainz, which enables measurements of long-lived actinide isotopes with minuscule sample sizes at the RISIKO mass separator, continued also in 2023. The data from previous measurement campaigns yielding nuclear moments and isotope shifts of the actinide isotopes $^{249-253}$Cf probed by laser spectroscopy was published [26]. A new measurement campaign that aims at probing the atomic and nuclear properties in ^{255}Fm was performed in 2023. Studies were expanded to explore the properties of Hg, Po, and At isotopes, serving as lighter homologs of the superheavy elements Cn, Lv, and Ts [27]. Work is ongoing towards the production of improved f-element targets for accelerator experiments, optimized for coping with highest beam intensities as they will become available, e.g., with HELIAC accelerator. Novel developments in electrochemistry were transferred to target production, employing anhydrous electrochemical routes [28]. A three-month campaign using the exotic 40-d ^{255}Es, made available by collaborative work with ORNL Oak Ridge (USA) and ILL Grenoble (F) that continuously yields the 20-h daughter isotope ^{255}Fm allowed complementing laser spectroscopy studies along a long isotopic Fm sequence by this neutron-rich isotope, and provided the basis for fundamental life science-oriented studies in cooperation with the GSI's biophysics department.

In 2023 the R3B set-up at GSI has been substantially upgraded to study quasi-free reactions in inverse kinematics. A method to evidence hypernuclear halos from a two-target interaction cross section measurement has been proposed and sensitivity of the method was investigated using a full simulation of realistic experimental configuration at R3B [29]. An experiment to search for the extremely neutron-rich oxygen isotopes has been carried out at the Radioactive Ion Beam Factory RIBF at Riken. ^{28}O and ^{27}O were observed for the first time through their decay into ^{24}O and four and three neutrons, respectively [30]. This result suggests that the Island of Inversion extends beyond ^{28,29}F into the oxygen isotopes.

Significant progress could be achieved in the description of the ejecta from neutron star mergers, which produce heavy elements through the rapid neutron capture process (r-process). In [31] it has been shown that for a reliable description of nucleosynthetic yields it is important to consistently consider all mass ejection channels and combine their respective production of heavy elements. A full modeling pipeline for kilonova emissions could be established, starting from hydrodynamical merger simulations, involving detailed nuclear network calculations, and feeding those data in radiation transfer codes [32]. One of the major improvements is the inclusion of a line-by-line treatment of atomic transitions in the radiative transfer calculations of the kilonova [33]. The opacities for single and double ionized neodymium and uranium have been computed [34]. The calculations show that Actinides may have substantially larger opacities than Lanthanides and consequently the calculations are being extended to include all Lanthanides and Actinides. Based on realistic spherically symmetric supernova models, the general existence of collisional instabilities around the neutrinosphere during the supernova accretion and postaccretion phase was shown [35].

The spectra of AT2017gfo was re-analyzed, which suggests that the outflow occurred in a very spherical manner [36]. Another study was devoted to a detailed analysis of thermal effects of hybrid equations of state, i.e. models with a phase transition to deconfined quark matter, in the context of neutron star mergers and the gravitational-wave emission [37]. The studies of gravitational wave emission from mergers of main-sequence stars and during the common envelope phase were performed in [38]. When considering compact dark objects in neutron star mergers it was concluded that such particular models of Dark Matter might be detectable with gravitational-wave detectors under optimistic assumptions [39]. The impact of pions in neutron star mergers was studied [40] and demonstrated that pions may have a sizable impact on for instance the gravitational-wave signal, the black-hole formation and the mass ejection and thus kilonova.

Understanding the origin of the matter–antimatter asymmetry and testing fundamental symmetries: A summary paper on the search for axion / axion like particle (ALPs) at COSY has been published [41]. The JEDI collaboration could for the first time establish a new complementary method to search for axion/ALPS. In 2023, two papers on the so-called pilot bunch method were submitted [42, 43]. At storage rings especially the sensitivity on the axion-nucleon coupling via the so-called axion wind term is enhanced be several orders of magnitude compared to other experiments because of the high velocity of the deuterons. This method could be employed at other storage rings like the ESR or CRYRING. Studies are going on to investigate the possibility of performing axion/ALP searches at the GSI storage rings. First results indicate that this seems to be difficult at the CRYRING because the low relativistic γ factor. It looks more favorable for the ESR.

Search for a variety of ultralight bosonic dark matter candidates was continued. While the dark matter was not found, a number of constraints reaching into hitherto unexplored parameter spaces have been published. The projects Cosmic Axion Spin-Presession experiments and the Global Network of Optical Magnetometers for Exotic physics searches were technically developed [44-57], and several ground-breaking proposals were published [58-60].

The construction of the P2 detector at the upcoming MESA accelerator in Mainz is progressing. P2 aims for a high precision measurement of the weak mixing angle at low energies, which has been funded in the framework of the Helmholtz Excellence network and the PRISMA+ cluster of excellence at Mainz University. The construction of the DarkMESA detector at the MESA accelerator in Mainz, for searching for light dark matter, had been pushed in the framework of the Helmholtz Excellence network.

The Borexino experiment took data from May 2007 until October 2021 using a 280-ton liquid scintillator (LS). In 2023, its final CNO measurement was published [61] and selected as an Editors' Suggestion. The zero-CNO hypothesis is rejected with a significance of more than 5σ, for the first time without any assumption on the backgrounds present in the detector. The sensitivity of JUNO to ^{7}Be, pep, and CNO solar neutrinos using solar neutrino spectroscopy was published. As a result, JUNO has a vast potential to exceed the precision of the existing Borexino measurement [62].

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4 Topic 3 – Matter and Radiation from the Universe

Participating Centers: DESY, KIT

The topic aims to fully exploit the potential of cosmic messengers. Neutrinos play a central role, and activities in neutrino physics pave the way for decisive experiments for dark matter searches. By combining the information from gamma rays, high-energy neutrinos, cosmic rays, and gravitational waves, and by precisely determining the properties of neutrinos and performing dark matter searches, all complemented by theoretical studies, the topic is developing a new picture of the high-energy universe.

High-energy neutrinos

The analyses of 11 years of data acquisition with IceCube as well as with the surface array IceTop are further progressing. The highlight in neutrino astronomy in 2023 was undoubtedly the detection of high-energy neutrinos from the galactic plane of our own galaxy with a significance of 4.5 sigma [1]. The signal is consistent with the diffuse emission of neutrinos produced in collisions of cosmic rays with interstellar gas in the Milky Way, but could also originate from a population of unresolved point sources. The discovery was only made possible by using deep learning methods to reconstruct the traces of signals in the ice. Also important were the first results of the new multi-sample measurement (global fit) where for the first time a break in the energy spectrum could be observed with a hard low-energy component below ~20-30 TeV and a softer high-energy component with a significance of about 4 sigma [2]. In [3], results of a stacking analysis of 29 TDE-like (Tidal Disruption Events) flares tested against the IceCube point source sample are presented, complementing the observations of IceCube alert neutrinos in coincidence with TDEs observed earlier (at 3.7 sigma). In 2023 the prototype station at the South Pole could be improved in hardware, and in the reconstruction procedures [4,5]. KIT showed an increased presence at the geographic South Pole by personnel staying the entire year and being responsible for monitoring the operation of the Observatory on site. The mDOM integration of the IceCube Upgrade continues at a steady pace. A total of 85 of 225 mDOMs have been completed and the production is well on track for shipping the first 128 mDOMs from DESY to the South Pole in 2024. Main focus of IceCube-Gen2 activities in the collaboration (including DESY and KIT) was the publication of the Technical Design Report [6], containing a complete description of the science, the technical design, and the performance of the instrument. It demonstrates the readiness of the collaboration to NSF and other funding agencies for the next steps towards the realization of the observatory. To bridge the gap between the completion of the IceCube Upgrade and the start of Gen2, the DESY group has started to prioritize the radio neutrino detection (RNO-G) activities that can directly be carried over to IceCube-Gen2. The RNO-G (Radio neutrino observatory in Greenland) detector is operating nominally, as earlier failures have been mitigated. According to schedule, there was no installation of new stations in 2023, at the same time the funding situation remains good, as a project lead Anna Nelles has been awarded an ERC starting grant. A detailed study of potential muon backgrounds for radio neutrino detectors has been presented [7], motivating more theoretical work (hadronic interaction models, pQCD calculations) at higher energies.

Direct Dark Matter search

A new laboratory for R&D on dark matter detectors has been set up at KIT in 2023, as a combined effort of MU activities with third-party and further seed funding activities. Important progress in the installation of key lab infrastructure was achieved, such as the implementation of a high-voltage test stand for qualification of large TPC electrodes in an argon flow atmosphere with light sensors for spark detection, the setup of a xenon gas handling and recuperation station, the assembly of the outer cryostat for the "MOTION" TPC designed to operate with up to 100 kg of xenon, and the preparation of a liquid-nitrogen supply line to service various R&D setups in the new laboratory from a storage vessel.

A large high-voltage electrode for the upcoming DARWIN observatory (2.6 m in diameter) is developed. First, electrodes of 1.4 m diameter are being produced, which can serve as spares for the XENONnT detector. KIT has completed design and main production steps of three electrodes using different technologies: a gate and anode (both wire grids) and a cathode (hexagonal-cell etched mesh). After successful test assemblies at KIT, these electrodes were brought to LNGS for final assembly and will be subject to rigorous cold tests in liquid xenon in spring 2024 at the PANCAKE platform at U Freiburg. This comprehensive qualification work will enter R&D efforts towards prototyping the larger 2.6 m electrodes. As preparatory work for DARWIN is progressing, analysis and data-taking of XENONnT are continuing with the goal of collecting a 20 ton-year total exposure. The XENON collaboration released the first nuclear recoil WIMP-search results based on the "Science Run Zero (SR0)" [8] which surpass the final results of the previous XENON1T detector by a factor of 1.6 at similar exposure of ~1 ton-year. Substantially larger data sets have been acquired since then in SR1 & SR2, at even further reduced ^{222}Rn backgrounds (now 50% lower than in SR0). In addtion, gradual gadolinium-doping of the water inside the XENON shield has started, with the goal of improving the neutron-tagging efficiency of the neutron veto detector and thereby reducing the neutron background by up to a factor of 3. KIT worked on dedicated studies for supernova detection sensitivity of XENONnT and its integration into the SNEWS network, with electric field simulations for the TPC, or with a study to optimize machine-learning analysis cuts. With major contributions from the KIT group, the description of design and performance of the XENONnT field cage [9], the improvement of the projected $0\nu\beta\beta$ sensitivity of DARWIN resulting from correcting an overestimation of the cosmogenic background from ^{137}Xe [10], and a quantitative assessment of potential underground laboratory sites for DARWIN based on background studies [11] have been published. A dynamic and distributed grid computing and analysis infrastructure for DARWIN has been set up at KIT. Furthermore, a community white paper about a next-generation liquid xenon observatory has been published [12] and a pre-proposal for DARWIN submitted for the Helmholtz Roadmap of Research Infrastructures was positively evaluated.

Neutrino physics with KATRIN

After the fourth year of neutrino-mass data-taking, 2023, KATRIN has recorded more than 10^8 β-electrons in the region of interest, in 11 campaigns. This progress corresponds to 60% of the goal of 1000 measurement days of beta-spectrum scans close to the kinematic endpoint of tritium by the end of 2025. For 2023, the successful operation on 252 days of scientific measurements exceeded the target of 210 days. For this performance, in sum 8.62 kg of tritium were circulated at an average of >98.4% purity in the tritium loop. This was accompanied by over 110 gas transfers from and to the tritium cleanup and enrichment facilities at the TLK [13].

In parallel to data-taking, the analysis of the first five campaigns will be concluded in early 2024. With regard to the last published result [14], statistical and systematic uncertainties will be reduced by a factor of six and three, respectively. The expected neutrino mass sensitivity of this upcoming release is better than $m_\nu < 0.5$ eV. Furthermore, searches for Lorentz-invariance violation [15] and for keV-scale sterile neutrinos [16], which resulted in new exclusion limits in the parameter space between 0.1 and 1.0 keV, were published. Preparations for upgrading the beamline in 2026 with the TRISTAN detector array are well on track and the Silicon Drift Detector production is finished. The upgrade will allow for extending the keV sterile neutrino search over the entire mass range up to 18 keV with a sensitivity increased by more than three orders of magnitude.

In a long-term perspective, achieving ultimate sensitivities in the neutrino-mass measurement below 40 meV via tritium beta decay will require the usage of atomic tritium instead of molecular tritium and a completely new class of high-resolution quantum sensors as detectors. First exploratory studies and R&D experiments started to evaluate an associated large-scale R&D program during PoF-V.

Gamma-Ray Astronomy

The preparations of the various in-kind contributions (Array Control And Data Acquisition system (ACADA), Medium-Sized Telescopes (MST), Small-Sized Telescopes (SST) cameras, Monte Carlo (MC) simulation pipelines) for the Cherenkov Telescope Array Observatory (CTAO) are ongoing. The Critical Design and Manufacturing Review of the MSTs was closed by the end of 2023 and the critical design review of the SST cameras will be performed in 2024. Meanwhile, DESY has started the procurement procedures for the two MST pathfinder telescopes. The foundation of the CTAO ERIC has hit an unexpected roadblock in summer 2023, as aspects of the CTAO ERIC application documents, related to ESO, were identified by the legal service of the European Commission as non-conforming with the ERIC regulations. This is a severe drawback for the current planning. To avoid further delays in construction, the shareholders of the current CTAO organisation have agreed to provide significant funds for 2024. Based on data from H.E.S.S., a publication on the Velar Pulsar [17] revealed measured energies up to 20 TeV from this class of objects. This observation is hard to reconcile with the theory of the production of such pulsed gamma rays and leaves room for further studies on this topic. The development of the ULTRASAT camera made good progress and construction has entered the production phase. A Single Event Effect (SEE) radiation test campaign of the sensor was held [18] and its results are currently under investigation. Moreover, the camera saw "First light" in 2023 which means that input of the sensor passes the entire readout-chain of the camera.

Ultra-high energy cosmic rays

A new era of data collection for the Pierre Auger Observatory has begun. All accessible water Cherenkov stations are equipped with scintillation detectors and improved electronics as part of the AugerPrime extension [19]. The additional complement of radio antennas is almost 50% deployed in the field. Only through the new electronics are all these additional components accessible. An international committee, led by Francis Halzen, enthusiastically recommended the extending data taking until at least 2035 - very favorably endorsed by the Auger Finance Board - due to the outstanding scientific quality and the expected significant improvement in the quality of the data and the results derived from it using state-of-the-art analysis methods such as machine learning. The high quality and wealth of detail was impressively exemplified by the publication of the 100 highest-energy events [20]. Particularly exciting is the observed behavior of the depth of shower maximum X_{max} (and of other composition-sensitive observables) with energy, which changes in an unexpected, non-trivial way. Around 3×10^{18} eV it shows a distinct change of the slope of the X_{max} vs. energy [21]. "top-down" source scenarios, such as the decay of super-heavy particles, cannot account for a significant part of the observed UHECR flux [22-25]. Although no discrete source of UHECRs has yet been identified, the extragalactic origin of the particles has recently been confirmed based on arrival directions above 8 EeV, and the selection of possible source regions at higher energies is gradually narrowing [21,22]. Additionally, the observatory has established a reputation as a test bed for the validation and calibration of prototype detectors for FAST, GRAND, IceCube and others. An interdisciplinary cooperation with collaborators from the Aeolus satellite led to a mutual calibration of the measuring instruments [26]. The Auger Collaboration is playing a leading role in shaping the future of the field by proactively participating in the development of national and international roadmaps for future scientific questions and infrastructures, such as [27].

Multimessenger Astronomy

DESY and KIT are continuing on the implementation of an analysis and data center for multi-messenger astroparticle physics. Significant progress was made in, e.g., the data broker service AMPEL (Alert Management, Photometry and Evaluation of Lightcurves) as well as by dedicated multi-messenger studies, like the correlation of high-energy neutrinos with gravitational wave emissions. AMPEL was stress-tested for LSST (Large Synoptic Survey Telescope) in a second edition of the ELASTiCC data challenge, with alerts simulated from the latest observation plan and delivered at even higher rates than in the first edition. The work is supported both by the NFDI consortium PUNCH4NFDI and by the ADC-MAPP project, funded by the so-called Innovation Pool for 2021-24. The general aim is to extend the existing approaches such as the KASCADE Cosmic-ray Data Center (KCDC), AMPEL or the analysis tool Gammapy into a coherent concept of a user facility.

Gravitational wave astronomy

Both groups at DESY and at KIT are "Research Units" of the Einstein Telescope Collaboration with seats in the Collaboration Board. The initiatives to advance contributions to the third-generation gravitational wave experiment are manifold and concern technological research and development in cryo- and vacuum technology as well as scientific studies on the sensitivity of the instrument, especially in multi-messenger astroparticle physics and concepts for future computing [28,29]. DESY together with partners from astronomy and astroparticle physics in Germany is strongly involved in the German Centre for Astrophysics (DZA), which is responsible for the preparation of the Low Seismic Lab, a shallow underground laboratory of the DZA with unique seismic properties, and for the investigation of Lusatia as a site for the Einstein Telescope. DESY scientists are active in the Observational Science Board to prepare the physics program of ET and in the Site Preparation Board to carry out studies at the Lusatia site. The KIT group is heavily involved in seismic measurements at possible sites and in activities at the Einstein Telescope Pathfinder facility in Maastricht. In addition, KIT scientists also contribute to the scientific portfolio of the DZA.

Theoretical Astroparticle Physics

KIT studied the following topics in 2023: decoherence in neutrino oscillations [30,31], statistical analysis of neutrinoless double-beta decay data and sensitivity estimates for future experiments [32], complementarity between cosmological and terrestrial neutrino mass determinations [33]. A significant activity has been devoted to long-lived particle searches (e.g. heavy neutral leptons [34], axion-like particles [35], Higgs-like scalars [36]), mostly in the GeV mass range. This includes the release of a public code to calculate sensitivity of generic beam dump experiments to this kind of new physics [37]. During a 3-months research stay at KIT by Michael Schmidt, UNSW Sydney, Australia, funded by a KIT international excellence fellowship, a joint publication on B-meson decays [36] was worked out.

The group at DESY worked on a manifold of topics and connected to various topics within the program. In 2023, two follow-up studies on the detection of neutrinos from tidal disruption events [38,39] and a paper that investigated a lepto-hadronic model for energetic GRBs [40] were published. This forms a theoretical framework for findings from the gamma-ray and neutrino experiments. In the area of gravitational waves, the group studied gravitational dynamics of binary systems relevant for present and future gravitational-wave detectors. A combination of theoretical approaches and techniques from particle physics leads to state-of-the-art in the analytic modeling of inspiralling compact objects, both in the Post-Newtonian and Post-Minkowskian expansions [41-43].

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5 LK-II Facility GridKa

Center: KIT

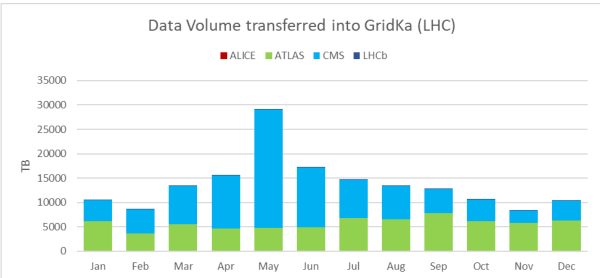
In 2023, GridKa provided the computing and storage resources with its usual high reliability. The LHC experiments, Belle II, and IceCube were provided with a total of 415 million core hours of computing time for 20 million computing jobs. The total resources of GridKa in 2023 comprised about 48,000 CPU-cores, 56 NVIDIA V100S and A100 GPU-cards, about 82 Petabytes (PB) scalable online disk storage (in which about 130 PB were written and more than 460 PB were read) and more than 120 PB reliable offline data storage for data archival. During the reporting period all services were provided smoothly to the experiments.

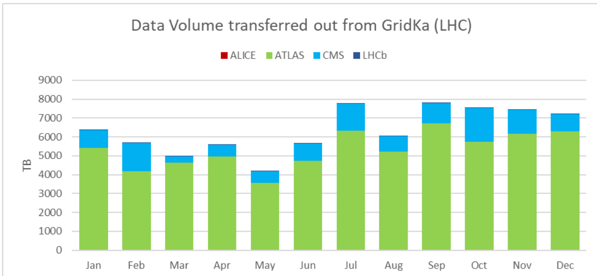
The GridKa batch farm was upgraded in terms of security software to replace the aging X.509 access mechanisms with modern token-based authentication/authorization methods. Due to foreseeable higher energy costs per kWh for 2023, a discussion and decision took place in the GridKa Overview Board in November 2022 to switch off more energy-consuming compute nodes for 2023 to stay within budget – this had absolutely no influence on fulfilling the pledges of GridKa resources to the international user community. Towards the end of the year a procurement was initiated for a few ARM based compute nodes, which will provide a ~20% higher computing performance per Watt.

The extension of the online storage system to 99 Petabytes was successfully finished after longer delivery delays for specific components and is in production since May 2023. The transfer of data from older storage systems was successfully finished until the end of the year. About 50 Terabyte of storage is newly available for the DARWIN experiment.

In the tape-based offline storage system, the migration activities from TSM to the HPSS technology dominated 2023. After CMS and LHCb in 2022, ATLAS is also finished, and the ALICE data are now being migrated. The new flash-based buffer in front of the tape system has been put into production and has significantly increased the overall performance.

The volume of data transferred to and from GridKa to other centers has remained at a very high level.





The joint development of the COBalD/TARDIS software for opportunistic computing was successfully continued. In a nutshell, this open-source software enables the dynamic, transparent and on-demand integration of distributed computing resources in the LHC computing environment. In a proof-of-concept computing resources from Lancium were successfully integrated – Lancium is a US/Texas-based company that operates computing centers next to wind turbines with excess renewable energy. Via COBalD/TARDIS these resources were opportunistically integrated in GridKa for MonteCarlo production – approximately 500,000 CPU-core-hours during the proof-of-concept. This demonstrated the possibility to operate parts of a WLCG Tier-1 center in a carbon-neutral way.

In addition, the close cooperation with the Helmholtz program "Engineering Digital Futures" (EDF) in the Research Field Information is successfully continued regarding the development of COBalD/TARDIS, European projects in the context of the European Open Science Cloud (EOSC), in the context of the National Research Data Infrastructure (NFDI) as well as in the context of ErUM-Data and related development projects. COBalD/TARDIS was used to build up the federated compute & data infrastructure in PUNCH4NFDI.

6 LK-II Facility GSI-MU Ion Facilities

Center: GSI

Rising costs for energy and materials in addition to extended construction works in the building of the UNILAC accelerator forced the GSI management to shift the planned user beam time for 2023. Instead of user operation an extended engineering run for accelerator tests and optimization. Hence, no beam time for scientific experiments on MU topics have been offered. The user beam time will start in February 2024 and will be continued in 2025 with an extension which will partially compensate the loss in 2023. All experiments rated with “A” by the Program Advisory Committees in 2022 could be scheduled during those beam times in 2024 and 2025. An additional four weeks were allocated and will be distributed in an extraordinary PAC meeting.

Accelerators: In the frame of dedicated machine experiments, new beam intensity records have been achieved in SIS18. Especially, at the demanding operation with low charge state heavy ions, e.g. U28+, which is dominated by charge exchange driven beam loss in a dynamic vacuum background, the former achieved world record has been exceeded. This is relevant for the later FAIR booster operation for SIS100. A new high frequency cavity has been developed, installed and commissioned. This cavity follows an urgent request of the users to improve the spill quality at slow extraction in the micro second regime. The cavity provides a partial or full bunching with a frequency of about 90 MHz during the slow extraction process leading to an enhanced duty factor and a smoother spill structure. After a major damage in 2023, saving the electrostatic wire septum of SIS18 was a general task and remains an issue especially for the high intensity runs. A dedicated collimator system generating a shadow for the septum shall provide the primary protection measure. However, there may also be indirect effects, e.g. gas desorption driven by the beam or HV break downs which shall be further investigated and controlled to protect the septum wires.

First approaches with machine learning applications for e.g. a fast injection setting optimization have been conducted. The goal of such and other, e.g. developments for beam based feed-back systems, is to enhance the efficiency of operation and to enable less setting-time and more beam-on-target time.

Experimental facilities: The experimental facilities of CML have been upgraded for the FAIR Phase-0 campaign in 2024. One decisive measure took place at the separator for super-heavy element production studies, SHIP. New power supplies for the quadrupole magnets were delivered and installed. The functionality of the new power supplies was tested at the engineering run in November 2023. Here, one day of ^{40}Ar beam was used with ^{169}Tm and ^{208}Pb targets. The obtained results of the fusion products in rate and spatial distribution match the expectations and thus SHIP is again ready for the upcoming physics beamtime 2024.

ALPIDE monolithic pixel sensors, which are planned to be utilized for the inner tracking system of ALICE@CERN, are considered to be used as tracking detectors at the fragment separator at the Super-FRS and have been successfully tested in an experiment at CERN. The ALPIDE sensors will also used in other experimental set-ups, and may serve as an example for the close link between experiments at GSI and GSI’s participation in ALICE@CERN.

IT: The Green IT cube offers more than 50,000 cores, 400 AMD Radeon GPUs and more than 60 PByte of storage space not only to the users of GSI experimental facilities but also for in-house theory groups running dedicated model codes. The network was upgraded and all systems were shut down for two weeks in April 2023. During this time, nearly all cables in the High Performance Computing systems were replaced with upgraded 200 Gb/s high-speed network HDR cables and connected to new HDR switches. Also in 2023, the AI innovation laboratory "GSI/FAIR Digital Open Labs" was officially established in collaboration with the Hessian Center for Artificial Intelligence "hessian.AI". The Digital Open Lab is meant to foster collaborations with industrial partners and research institutions, and serves as a contact point in this field for more than 70 companies, start-ups and scientific institutions to share the unique IT infrastructure. DC Smarter, a German IT start-up, was one of the first industrial partners. The company provides solutions for optimization of central services in a data center by employing Digital

Twins and Augmented Reality. These concepts are tested together with IT GSI's department in the Green IT cube.