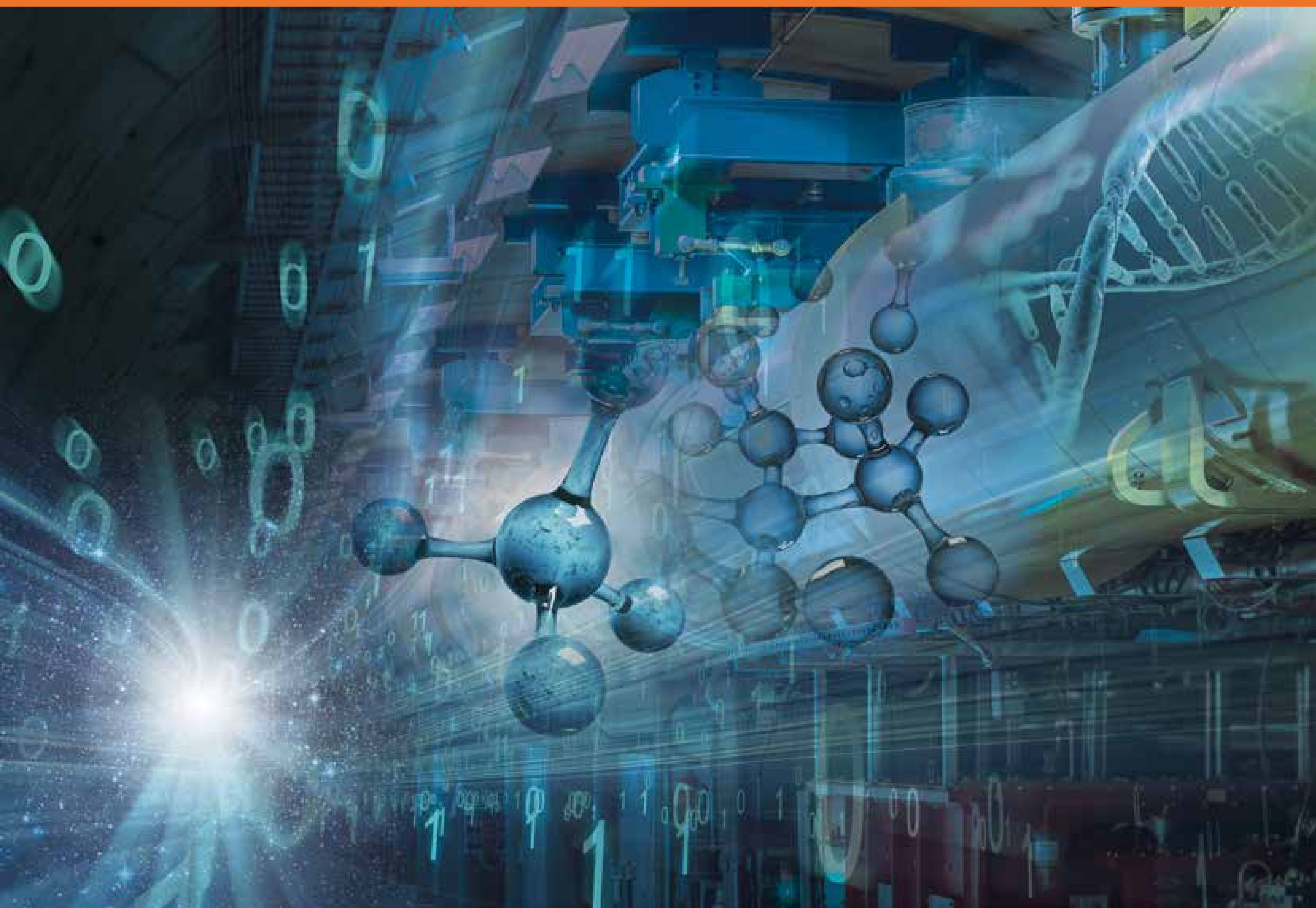
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

OVERVIEW

Research Field MATTER
Strategic Evaluation for the Fourth Period of Program-oriented Funding, 2021 – 2027



HELMHOLTZ ASSOCIATION

We contribute to solving the major and pressing problems of society, science and industry by conducting high-level research in the strategic Programs of our six Research Fields: *Energy*; *Earth and Environment*; *Health*; *Aeronautics, Space and Transport*; *Matter* and *Information*.

We research highly complex systems in cooperation with national and international partners using our large-scale facilities and scientific infrastructure.

We are committed to shaping our shared future by combining research and technological developments with innovative applications and prevention strategies.

We seek to attract and promote the best people and offer our staff a unique scientific environment and comprehensive support in all stages of their development.

RESEARCH FIELD *MATTER*

Helmholtz Vice President and Research Field Coordinator

Prof. Dr. Dr. h.c. Helmut Dosch

Participating Helmholtz Centers

DESY Deutsches Elektronen-Synchrotron

FZJ Forschungszentrum Jülich GmbH

GSI Helmholtzzentrum für Schwerionenforschung GmbH

HI Jena Helmholtz-Institut Jena
HIM Helmholtz-Institut Mainz

HZB Helmholtz-Zentrum Berlin für Materialien und Energie

HZDR Helmholtz-Zentrum Dresden-Rossendorf

HZG Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research

KIT Karlsruhe Institute of Technology

IPP Max-Planck-Institut für Plasmaphysik

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1. EXECUTIVE SUMMARY

In the Research Field *Matter*, the Helmholtz Association bundles its expertise in research on matter, in the construction and operation of complex large-scale research facilities for fundamental and applied sciences, and in the development of basic technologies such as new accelerator, detector and data management concepts.

Together with the financing partners, we have worked out the strategic goals of the Research Field *Matter*. This document describes the measures how these goals will be reached.

The scientific mission of the Research Field is to investigate the structure and properties of matter. In the coming years, the following key questions will be in the focus of research:

- How has the universe developed from the big bang to the present day?
- What are the building blocks of matter and their fundamental interactions, and what is the origin of the elements in the universe?
- How can electronic and molecular processes on all relevant length and time scales be better understood and controlled as prerequisite for the development of novel functional materials and better-tailored drugs?
- How can highly brilliant and compact particle accelerators and modern detectors and sensors be developed and their data be harvested for research and industry?

The quest to answer these questions leads into quantum worlds, which are most challenging to access conceptually and experimentally, but bear the potential for both fundamental discoveries and essential contributions to solving the great challenges of today and tomorrow. The Research Field and its eight centers are excellently positioned to play a world-leading role in tackling these challenges.

Further strategic goals of the Research Field are the continuous development of its mission-critical research infrastructures, national and international cooperation, transfer to industry and society, talent management, and increased cooperation across disciplines, especially in materials research, structural biology, radiation research, and quantum technology.

One of the major challenges the Research Field *Matter* will face in the coming years is the large amount of complex data generated at its modern large-scale facilities. In consequence, the Research Field has taken several steps to meet this challenge, in particular by establishing the new Topic *Data Management and Analysis* in the Program *Matter and Technologies* (MT-DMA), in which all centers of the Research Field cooperate. MT-DMA will closely collaborate with the new Research Field *Information*. The Tier-1 center GridKa and the new Interdisciplinary Data and Analysis Facility (IDAF, former Tier-2 center) are prepared to meet the upcoming challenges.

2. OVERVIEW OF THE RESEARCH FIELD *MATTER*

Within the Research Field *Matter*, the Helmholtz centers DESY, FZJ, GSI, HZB, HZDR, HZG, IPP, and KIT bundle their complementary expertise and make focused and dedicated use of large-scale research facilities, which they continuously develop further. Figure 1 shows a map of the eight centers and a summary table of their large infrastructures. The Helmholtz Institutes Mainz and Jena belong to GSI.

	LK II (User facilities)	International Research Infrastructures	National Research Institutes/ Infrastructures
DESY	FLASH PETRA III IDAF	LHC Belle II CTA (*under construction*) IceCube European XFEL ESRF	CFEL CSSB NanoLab DESY Test Beams DAF HIB@European XFEL PITZ
FZJ	JCNS (in MLZ)	ESS (*under construction*) ILL	(FRM-II)
GSI	UNILAC SIS18 ESR	FAIR (under construction) ALICE@LHC	HI Jena HI Mainz
HZB	BESSY II / BESSY VSR		bERLinPro SupraLab EMIL
HZDR	ELBE HLD IBC	European XFEL EMFL ESRF	HIB@European XFEL DRESDYN
HZG	GEMS	ESS (*under construction*)	EMSC
IPP		PAX/APEX	
KIT	GridKa	KATRIN Auger IceCube	ATP FLUTE TLK SR Beamlines

Figure 1: Map of the Helmholtz centers contributing to the Research Field *Matter* and table of their research infrastructure portfolio in the program-oriented funding period IV (2021–2027).

2.1. Mission

The scientific mission of the Research Field *Matter* is to explore the structure and properties of matter. This includes investigations on all length and time scales, from the elementary building blocks of matter and the exploration of the quantum world to fundamental questions of the development of the universe. The understanding of complex interactions and processes at different length scales also serves as a basis for the development of new materials and drugs. The centers have devised and implemented an efficient interdisciplinary cooperation structure with the aim to create added value in science, technology development and transfer, as well as in talent management.

2.2. Positioning in the national and international context

The research portfolio of the Research Field and the close interdisciplinary cooperation of several centers are pioneering on the international level. The Program structure implemented in PoF III is unique in the world as it allows the close interdisciplinary collaboration of many different research disciplines. In close coordination, the Research Field operates state-of-the-art research infrastructures that have an impact on a world level.

The research infrastructures of the Research Field are essential to fulfill the Helmholtz Association's internationalization objectives. With its diversified cooperation within international large-scale research projects, particularly in particle and astroparticle physics, the Research Field makes an essential contribution to the Helmholtz mission and to strengthening the German science location.

The user operation of our research facilities (performance category LK II) is particularly beneficial for university scientists, because the Research Field offers them a unique and internationally leading research infrastructure to carry out their research projects. This is a paragon for successful international cooperation based on a proper assignment of tasks between the centers of the Helmholtz Association and the universities.

The Research Field assumes an architect role in the design of the European research area: Currently, the Research Field coordinates the European initiative LEAPS (League of European Accelerator-Based Photon Sources) to enhance the cooperation and integration of the national research facilities (common standards, technology roadmaps, agreement in the scientific portfolio). The League of advanced European Neutron Sources (LENS) was founded to similarly integrate the neutron community, in which the Research Field *Matter* plays an active role. Recently, the European Magnetic Field Laboratory (EMFL) collaboration developed a high magnetic field strategy for Europe for the next ten years. Likewise, the Research Field *Matter* helps to shape the science programs for particle and astroparticle physics and for nuclear and hadron physics, which are coordinated by the international bodies CERN Council, ECFA/ICFA, APPEC, and NuPECC.

We see our modern research infrastructures, including our ambitious research program, as main attractors for junior researchers from Germany and abroad.

2.3. Role of infrastructures

Design, construction, and operation of complex large-scale research facilities are a core competence of the Research Field. They are vital for implementing our own research targets, and they provide access to national and international teams of researchers after a corresponding peer review procedure. Every year, more than 10,000 scientists use our modern experimental stations. Indeed, at most of the facilities, the time available for experiments is overbooked several times, with increasing tendency. Research at the Helmholtz large-scale facilities is thus the paradigm of a highly efficient cooperation strategy between universities and non-university research institutes.

With a complementarily organized portfolio of large-scale research facilities, the Helmholtz Association plays the role of an architect of the worldwide science landscape. The large-scale facilities of the Research Field are interdisciplinary research platforms that are indispensable in projects of physicists, chemists, biologists, geo- and materials scientists and in many other disciplines of basic and applied research. They offer one-of-a-kind research possibilities particularly to junior scientists at universities. The advantages of non-destructive *in situ*, *in vivo*, and *operando* analytics are also increasingly being used in industry-related research. In the future, the access of industry to large-scale research facilities will move more and more into focus.

The centers of the Research Field *Matter* are strategic partners of renowned international large-scale research facilities in particle and astroparticle physics and initiators of the two international research facilities European XFEL in Hamburg and FAIR in Darmstadt.

The design, construction, and (user) operation of large-scale facilities and the strategic cooperation with international large-scale research facilities are a unique feature of the Helmholtz Association, which substantially contribute to the international competitiveness of the German science location. In order to keep an international top position, these complex research infrastructures must be continuously advanced. This requires long-term strategic planning.

2.4. Research Field costs

The following table shows the planned costs of the research centers in the Research Field *Matter* that will be covered by institutional core-funding in 2021 (on the 2020 price basis – without increase). Please note the used notation which applies to the entire proposal: Costs are given in thousand euros (TEUR), and for all resource numbers the thousands separator is a dot, and the decimal separator is a comma.

Table 1: Full costs of the Research Field Matter as starting point for PoF IV.

TEUR	DESY[1]	FZJ	GSI[2]	HZB	HZDR	HZG	IPP	KIT	TransFAIR (FZJ/GSI)[3]	Total
Matter and the Universe (LK I)	47.449		15.044				3.800	23.868	3.849	**94.010**
Matter and Technologies (LK I)	24.896	1.445	8.409	13.666	11.399	403		19.725	1.029	**80.971**
From Matter to Materials and Life (LK I)	27.742	13.281	14.169	7.356	23.343	2.285		8.709		**96.885**
Accelerator of European XFEL (DESY)[4]	63.216									**63.216**
FLASH (DESY)	44.365									**44.365**
IDAF (DESY)	6.406									**6.406**
PETRA III (DESY)	63.981									**63.981**
JCNS (FZJ)		20.000								**20.000**
FAIR (during construction) (GSI/TransFAIR (FZJ/GSI))[5]			63.276						9.523	**72.799**
GSI-MML Ion Facilities (during construction)[6]			8.789							**8.789**
GSI-MU Ion Facilities (during construction)[6]			23.579							**23.579**
BER II (HZB)[7]				24.006						**24.006**
BESSY II (HZB)				48.718						**48.718**
ELBE (HZDR)					10.844					**10.844**
HLD (HZDR)					7.695					**7.695**
IBC (HZDR)					10.248					**10.248**
GEMS (HZG)						6.219				**6.219**
GridKa (KIT)								7.296		**7.296**
Total	**278.055**	**34.726**	**133.266**	**93.746**	**63.529**	**8.907**	**3.800**	**59.598**	**14.400**	**690.027**

1 *The DESY numbers do not include a recently decided annual reduction of 2.000 TEUR. This amount is distributed proportionally among all DESY activities (excluding Accelerator of European XFEL).*
2 *Thereof, HI Jena is included with 4.974 TEUR in the costs of the program MML and 3.189 for the program MT, respectively. HI Mainz contributes with 5.464 TEUR in the costs of the program MU and 870 TEUR for the program MT, respectively.*
3 *Special regulation: The TransFAIR program costs do not include noncash expenditures and costs for infrastructure. The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.*
4 *The responsibility for the facility's overall operation and development is with the European XFEL GmbH, the operation and development of the accelerator are mandated to DESY. The total Helmholtz contribution including DESY to the operation costs of European XFEL are shown for information and are exempt from the PoF evaluation process.*
5 *During PoF IV, preparations and start of FAIR are planned. This part of the GSI base funding is exempt from the PoF evaluation process.*
6 *During FAIR preparations, GSI's user facilities deliver a reduced amount of beam time; in PoF IV they are exempt from the LK II regulations.*
7 *BER II has ceased user operation end of 2019 and is entering the post-operational phase beginning of 2020.*

3. CHALLENGES OF THE COMING 5 – 10 YEARS

Key scientific challenges that will be addressed by the Research Field *Matter* in the next funding period include first answers to the following questions (see Chapter 3.1.):

- How has the universe developed from the big bang to our days – what are the building blocks of matter and what is the origin of the elements in the universe?
- How can we understand and control electronic, atomic, and molecular processes at all relevant length and time scales for fundamental science and for the development of advanced materials and better drugs?
- How can we devise novel high-gradient particle accelerators and detectors with ultimate resolution in time, space, and energy for research and industry?

The Research Field has identified the handling of the highly complex large-scale data sets that will emerge from the advanced facilities in particle and astroparticle physics as well as from synchrotron radiation and free-electron laser (FEL) facilities as a major challenge in the upcoming funding period that requires particular attention. This will be addressed in more detail in Chapters 3.2 and 3.4.

Further challenges of the Research Field *Matter* concern the development of its large-scale facilities and the participation in international large-scale projects. This will be further discussed in Chapters 3.3 and 4.3.

The transfer of knowledge and emerging technologies to society and to the market is an increasing strategic activity in the Research Field *Matter*, as discussed in some detail in Chapter 4.5.

Finally, the global competition to attract the best brains is a continuous challenge, also in the upcoming funding period. We address this challenge in Chapter 4.6.

3.1. Scientific goals

The scientific goals of the next decade are the following:

- **We explore the limits of the Standard Model of particle physics**
  The Higgs boson discovered at the LHC at CERN opened up completely new perspectives for testing the Standard Model of particle physics and for searching for physics beyond the Standard Model. The LHC is the only facility worldwide to allow such studies at highest energies and smallest length scales. Complementary tests of the Standard Model are made possible by extreme-precision measurements on heavy quarks. Neutrinos also confront us with unsolved mysteries. Their properties and various roles from the big bang to stellar explosions are still not understood. What is the neutrino mass? Are there more than the identified three kinds of neutrinos? The universe consists of only five percent of normal matter, the remaining 95% we understand only rudimentarily. What is dark matter, which is so far revealed only by gravitation?
- **We investigate the complexity in hadrons and nuclei and their role in the universe**
  Quantum chromodynamics (QCD) is established as a fundamental theory of the strong interaction. But how does the complexity we observe in the structure and dynamics of hadrons and nuclei emerge from the quark and gluon degrees of freedom in QCD? What are the properties of the proton and neutron, the fundamental constituents of atomic nuclei, and how can their interaction be derived from QCD? What does the phase diagram of nuclear matter look like? Which role do hadrons, nuclei, and nuclear matter play in the evolution of the universe and the creation of the elements? How do the structure of neutron stars and the dynamics of neutron star mergers connect to the QCD phase diagram and the properties of dense hadronic matter?

- **We explore the origin of the various kinds of cosmic radiation**
  The universe is full of high-energy radiation such as photons, charged particles, and neutrinos. Their energies reach up to a hundred million times the ones produced by our terrestrial particle accelerators. How does nature achieve this? What are the sources of cosmic radiation? How can we solve the puzzle by means of repeated observation of the various kinds of particles?
- **We analyze matter under extreme and non-equilibrium conditions**
  The properties and behavior of matter and materials at extreme temperatures and pressures and in interaction with strong external fields are mostly unexplored. One of the pressing questions is whether there are emergent functions under non-equilibrium conditions that can be utilized for future applications.
- **We map dynamical processes on atomic time and length scales**
  How can we map important processes in materials and at the surface of materials on the atomic time and length scale? Will it help to derive strategies on how to control material properties and processes on the level of single atoms, electrons, and spins?
- **We interrogate complex (functional) materials for new applications**
  The coming decade will be dominated by complex materials that are multifunctional and blur the delimitations between metals, isolators, semiconductors, and organic-biological systems. This requires novel interdisciplinary strategies for synthesis and non-destructive *operando* analysis.
- **We decode complex biological structures and processes**
  Structural biology faces a change of paradigms caused by the enormous successes in the development of cryo-electron microscopy and the new possibilities provided by the European XFEL X-ray laser. Live fluorescence microscopy now allows real-time visualization of protein dynamics in response to DNA damage produced by heavy charged particles. With the revolutionary concept of serial femtosecond crystallography at FELs, it is possible to record biological molecular structures and processes in their native surroundings and in real time. The application of all these techniques will allow us to bridge the resolution gap from entire cells down to the molecular and atomic level.
- **We explore the physical limits of particle acceleration**
  We must further optimize accelerator technology in order to keep the existing (such as European XFEL) and future (such as FAIR) user facilities at the top of global research. For future experiments, we will generate and characterize particle beams of highest density, highest performance, highest brilliance, and ultrashort pulse length in the attosecond range. The further development of superconducting accelerator technology continues to be a central challenge.
- **We push plasma acceleration to application**
  The plasma-based acceleration of charged particles opens the way to novel ultracompact accelerators. Much progress in the understanding of accelerator mechanisms and the physics of plasma is necessary to bring this revolutionary technology to application maturity.
- **We investigate novel sensor materials and detector systems**
  Sensors are the central part of our detectors. We will advance the development of innovative sensors and complete detector systems that will make possible the ultimate energy and spatial resolution near the quantum noise. We will individually tailor the properties of semiconductor sensors in particular according to the specific experimental requirements.
- **We push the limits of knowledge extraction**
  Our facilities and experiments provide high-quality data – both real and model-based – of unprecedented complexity and volume at ever increasing rates. We will heavily invest in people and in developing advanced methods for extracting the scientific knowledge from these resources, while providing software and hardware infrastructure that will enable scientists to optimally deal with the future volume, variety, velocity, and veracity of scientific data in the Research Field *Matter*.

3.2. Technological challenges

To achieve our goals, we must create the necessary technological preconditions. This generally involves pushing the limits of what is technically feasible. In the coming years, we will address the following challenges:

- **Construction and implementation of the experiments for the HL-LHC**
  The planned high-luminosity operation of the LHC confronts the detectors with enormous challenges. Construction and commissioning of the detectors are central goals of the coming years. Here, the Research Field *Matter* will assume a central role in Germany and worldwide.
- **Development of novel sensors and detector systems for future experiments**
  With the rapidly increasing performance of accelerators and radiation sources and the advent of large new observatories, detector systems and the gain of knowledge from data must keep pace. We will massively increase the number of pixels and the integration density of particle and X-ray detectors, allowing us to develop detectors of so far unrivalled capacity.
- **Technology development for the advancement of accelerator facilities**
  To adapt the accelerator facilities of our Research Field to the ever-increasing user requirements regarding the performance parameters, we will develop the superconducting radio frequency technology for efficient continuous-wave (CW) operation as well as new concepts and technologies to fulfill the increasing demands concerning beam intensity, stability, and quality. We will further advance our methods and techniques for the diagnosis and control of particle beams.
- **Demonstration of a compact plasma accelerator for FEL and electron test beams**
  An important step towards the use of plasma acceleration is to demonstrate its application in an accelerator under realistic conditions. For this purpose, we will develop a concept for this kind of accelerator. Our target is to realize – in international cooperation – an accelerator together with the users.
- **Digitally organizing our data**
  Optimum knowledge extraction from data demands extremely powerful infrastructure and methods and software development to go hand in hand with the needs of facilities and scientific communities. We will provide modular, reusable technologies for integrated digital infrastructures for all scientific areas in the Research Field *Matter* and respond to their diverse scientific needs by systematically developing our already excellent capabilities.

3.3. Further development of large-scale facilities

The mission of the Research Field *Matter* is critically coupled to the use of large-scale research facilities that operate at the limit of current technologies (see Chapter 4.3). In the upcoming funding period, this implies *inter alia* urgent upgrades of existing large-scale facilities. In what follows, we summarize the planned facility upgrades and our participation in the construction of international facilities and in the preparation of technical design reports (TDR) and feasibility studies for potential future facilities.

Upgrades of national facilities

- **BESSY VSR and BESSY III**
  Within the upcoming funding period (2021–2027), the new BESSY VSR technology will be installed in the existing storage ring and commence user operation. BESSY VSR will enable time-resolved studies down to the picosecond time scale. The conceptual design report (CDR) for a new soft X-ray facility (BESSY III) based on multibend achromat technology will be completed by the middle of the PoF IV period at the latest, and a corresponding TDR in the second half of the PoF IV period.
- **DALI**
  The Dresden Advanced Light Infrastructure (DALI) is the conception of a follow-up of the ELBE facility. It aims at satisfying the scientific requirements of users at existing IR/THz radiation sources on a globally exceptional level also beyond 2025. The focus of the facility will be the application of extremely intense, pulsed, and flexible – with regard to

repetition rate, bandwidth, polarization, pulse form, and pulse delays – radiation in the IR to THz spectral range in materials and life sciences. Moreover, an option for extending the concept to the VUV range is under discussion. In parallel, the experimental stations will have access to high-performance laser beams and pulsed magnetic fields, thus facilitating unique sample environments. A CDR will be brought to completion in the first year of PoF IV.

- **FLASH2020**
  The soft X-ray laser FLASH will undergo an upgrade. This includes a number of measures, among others the installation of an undulator with variable magnet gaps in FLASH1 and the implementation of a seeding technology to enhance the spectral beam characteristics. Together with European XFEL, a concept is to be worked out to increase the pulse repetition rate of FLASH up to a CW operating mode.
- **PETRA IV**
  In order to keep PETRA III on a world-leading level, it is absolutely necessary to upgrade the storage ring to the multibend achromat technology. The predesign study shows that it will be possible to devise a synchrotron radiation source with ultimate emittance and diffraction-limited beam characteristics in the X-ray regime, and to implement it into the existing ring tunnel. The CDR was completed at the end of 2019, the TDR-phase will start in 2020. Construction of the critical parts of the new storage ring should start in 2022; the implementation of the storage ring into the existing tunnel is foreseen between 2024 and 2027, with a dark period of the research facility of two years.

Participation in the construction of international facilities

- **FAIR**
  The completion and commissioning of FAIR will be a milestone for the global science community, further broadening the scope of hadron, nuclear, and atomic physics into more interdisciplinary research on the properties and evolution of matter in the universe, and driving applications in other Research Fields, serving society and technology.
- **CTA**
  The international CTA observatory will be built in the coming years with leading participation of DESY. CTA will be the first research infrastructure in astroparticle physics to be operated as an open observatory, combined with the research and data center at DESY in Zeuthen.
- **ESS**
  Since 2014, the most powerful neutron source in the world is being built in Lund, Sweden, with strong German contribution. Currently, 15 instruments are being constructed by European consortia. German partners (BMBF, FZJ, HZG, and Technische Universität München) participate in seven of these projects, with a leading role in six of them. Commissioning with beam for some of the instruments will start in 2022, the user program in 2023.
- **IceCube-Gen2**
  With IceCube-Gen2, by the end of the next decade, a worldwide unique neutrino observatory at the geographic South Pole will be made available to the international research community for interdisciplinary use. DESY and KIT play a central role in the technology and project development and work together on the realization of the project in close coordination with national and international partners.

Technical design reports and feasibility studies for possible future facilities

- **HBS prototype**
  One part of the neutron strategy is the development and implementation of compact accelerator-based neutron sources, which, through the optimization of their brilliance, will allow experiments complementary to ESS, ILL, and other sources. Thanks to their scalability, HBS-type sources will have a broad application spectrum. This novel concept is to be confirmed by a prototype. The CDR of the full-scale facility will be finalized in 2019 and be followed by a detailed technical report (FZJ).

- **IAXO**
  The International Axion Observatory (IAXO) will be the first "medium-scale" experiment for the search of new and very light elementary particles – so-called axions and axion-like particles. These particles are candidates for dark matter, whose emission from the sun would be traceable with IAXO. Thanks to its existing infrastructure, DESY is an ideal location for this planned experiment. Until 2020, a TDR will be brought to completion and a first demonstrator experiment could be tested.
- **GCOS**
  If the Pierre Auger Observatory, with the help of the AugerPrime upgrade, should find clear indications of the direction of sources of ultra-high energy cosmic radiation, the Global Cosmic Ray Observatory (GCOS) should be envisaged for a thorough investigation of these sources. The leading center would be KIT.
- **DARWIN**
  For the ultimate search for heavy particles of dark matter, a time projection chamber of several tens of tons of liquid xenon will be developed in international cooperation. A realization could be possible by the end of the PoF IV period (KIT).

3.4. Data management and analysis

Our future experiments will produce huge amounts of complex data, which are processed in globally networked infrastructures (dedicated large-scale computer centers as well as Tier-1 GridKa and Tier-2 centers). From these data, complex algorithms generate new knowledge about the microcosm. Because of their enormous scientific spectrum, our large-scale facilities pose unique challenges in data management and analysis, from high data rates in real-time analysis systems through complex big data analysis methods and algorithms up to data management for heterogeneous international research groups. In future, new advanced high-speed megapixel detectors will create enormous challenges in online visualization, data storage, and data processing.

The centers of the Research Field have taken measures to address these challenges, including the establishment of the new Topic *Data Management and Analysis* in the Program *Matter and Technologies* (MT-DMA), which bundles the data and computing competences of the Research Field *Matter*. MT-DMA will create a close link to the new Research Field *Information*. The Tier-2 center at DESY will be extended and become the Interdisciplinary Data and Analysis Facility (IDAF), which will also serve new large-scale photon science facilities such as the European XFEL and PETRA IV. In MU, the Tier-1 center GridKa at KIT is prepared to meet the upcoming challenges.

Furthermore, the Research Field is participating in two new Helmholtz Information & Data Science Schools (HIDSS) in Hamburg (DASHH) and Berlin (HEIBRIDS) devoted to the training of a next generation of scientists. The training modules include algorithm development, machine learning, and real-time visualization schemes.

4. FUTURE THEMATIC AND PROGRAMMATIC POSITIONING

At the beginning of the current PoF III funding period (2015–2020), the Research Field adopted a modern and trend-setting Program structure, based on the close cooperation between the centers and the building of bridges between basic research, application-oriented research, and technology development. Within this elaborated Program structure, research activities are coordinated within three interdisciplinary Programs: *Matter and the Universe* (MU), *From Matter to Materials and Life* (MML), and *Matter and Technologies* (MT). The Program structure has already proved very successful in the current funding period. For PoF IV, the scope of the Program Topics will be partly retailored, following the strategy of the Research Field to respond to the upcoming challenges.

4.1. Overview of the Research Field *Matter* in PoF IV

Figure 2 shows the structure of the Research Field *Matter* with its Programs, Topics, and LK II infrastructures. (LK I refers to research, LK II refers to user facilities.)

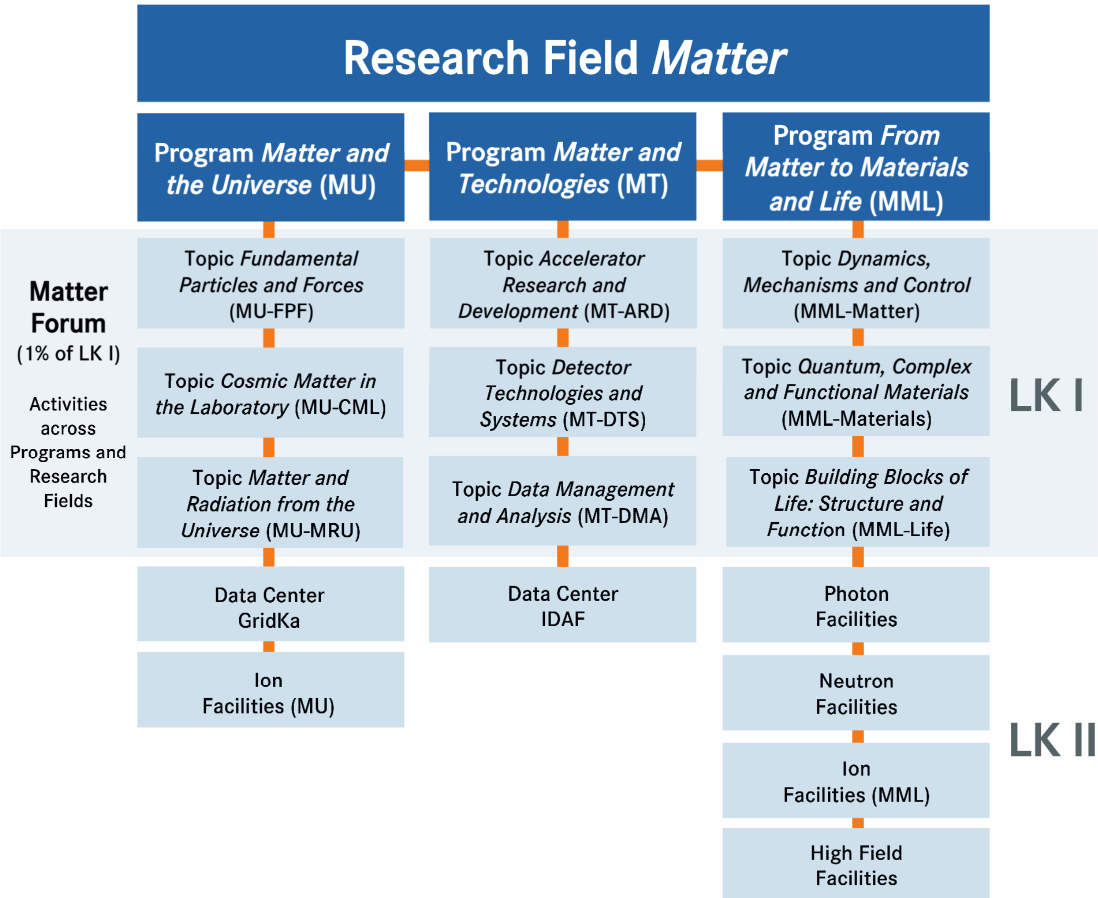

Figure 2: Program structure of the Research Field *Matter* for PoF IV (2021–2027).

Several structural changes within the Research Field *Matter* (see Table 2) are planned for the new PoF period, which will start in 2021:

In the Program MU, the Topic structure remains unchanged. On the Subtopic level, a dynamic adaptation will take place with advanced or new projects. Moreover, the LK II infrastructures of GSI will again be made available for research.

In the Program MML, the Topics were bundled more strongly to adapt to the future challenges. The single PoF III Topic, consisting of five research themes, will be replaced by three Topics. In addition, the LK II infrastructures of GSI will again contribute to the MML Facility Topic *Ion Facilities*.

In the Program MT, a new Topic called *Data Management and Analysis* (MT-DMA) will be implemented. MT-DMA will concentrate research, competence, and resources in scientific and data-intensive computing across all centers of the Research Field. MT-DMA will deliver open, reusable, and modular solutions to the challenges of high-rate, high-volume, and high-complexity data produced by facilities, experiments, and simulations specific to the Research Field *Matter*.

The scope of the Tier-2 center at DESY will be extended, and the center will be renamed to Interdisciplinary Data and Analysis Facility (IDAF) and transferred to the Program MT.

Table 2: Overview of structural changes in the Research Field *Matter* for PoF IV (2021–2027).

Structural Changes of the Research Field *Matter* for PoF IV	Involved Research Fields	Involved Programs	Involved Topics	Involved Centers
Introduction of the new Topic **DMA**	*Matter*	MT	MT-DMA	DESY, FZJ, GSI, HZDR, HZB, HZG
Transfer of the **Tier-2 data center** from the Program MU to the Program MT (new name: **IDAF**)	*Matter*	MU, MT	–	DESY
Transfer of the **Biophysics Department** at GSI from the Research Field *Health* to the Research Field *Matter*	*Health*, *Matter*	MML	MML-Life	GSI
Transfer of research activities on **magnetohydrodynamics** at HZDR from the Research Field *Energy* to the Research Field *Matter*	*Energy*, *Matter*	MML	MML-Matter	HZDR
Transfer of the research activities on **plasma physics** at **IPP** from the Research Field *Energy* to the Research Field *Matter*	*Energy*, *Matter*	MU	MU-MRU	IPP
Transfer of the **IKP** from FZJ to GSI within the Research Field *Matter* (TransFAIR FZJ/GSI)	*Matter*	MU, MT	MU-CML, MT-ARD, MT-DTS	FZJ, GSI

The Biophysics Department at GSI will be transferred from the Research Field *Health* to the Research Field *Matter* into the Topic Life of the Program MML. The department studies the action of heavy ions on biomolecules, cells, tissue, animals, and humans. Main applications are charged-particle therapy in oncology and radiation protection in space travel. The department is divided into eight groups covering experimental and modeling methodologies from molecular biology to atomic and nuclear physics.

New in the Topic MML-Matter is HZDR's research on magnetohydrodynamics (MHD), based on a worldwide unique experimental platform for research on conducting fluids. The focus of this research addresses the origin of cosmic magnetic fields in planets, stars, and galaxies produced by the dynamo effect, and the subsequent role that these fields play in cosmic structure formation by means of the magnetorotational instability that triggers mass accretion onto protostars and black holes. This astrophysical MHD effort is synergistic with research in the Program MU on cosmic-ray acceleration at IPP.

In order to strengthen and benefit from synergies within the Helmholtz Association, specific fundamental research activities in plasma astrophysics and astroparticle physics of the Max-Planck-Institut für Plasmaphysik (IPP) in Garching and Greifswald will be transferred from the Research Field *Energy* to the Research Field *Matter*. The IPP will henceforth represent the eighth Helmholtz center within *Matter*. It will be fully integrated within the existing structure in the Program MU. Research will be carried out in close collaboration with Topics of the Programs MML and MT.

It is planned to transfer the activities of the Institut für Kernphysik (IKP) from FZJ to GSI (except for the theory institute IKP-3). The transferred IKP activities (TransFAIR FZJ/GSI) will focus on the realization of the High Energy Storage Ring (HESR) and on major components of the PANDA detector at FAIR. Moreover, they will address precision physics experiments, in particular with polarized particles. The TransFAIR FZJ/GSI activities, which are carried out in close cooperation with the universities of Aachen, Bochum, Bonn, Cologne, Düsseldorf, Mainz, and Münster, are embedded in MU and MT. The full competences of the IKP will thereby be retained within the Helmholtz Association.

Several facilities and activities will be phased out in the next years in order to enable a new programmatic positioning of the Research Field *Matter* in the future:

- **MU (DESY):** Resources from the ILC preparatory project will be transferred to the new Topic MT-DMA.
- **MU (GSI/FAIR):** The major focus of GSI will be the completion and commissioning of the FAIR facility. In parallel, an intermediate LK I research activity and a limited LK II user program, called FAIR Phase 0, will be pursued at the GSI accelerators. With the start of installation of the new experimental setups at the FAIR facility around 2023/24, large parts of the GSI experimental activities will be relocated to the respective FAIR experimental stations.
- **MU (KIT):** The dark matter experiment EDELWEISS will be phased out in 2019. The KIT contribution to EDELWEISS has already been reduced during the last years. In turn, KIT is building up its participation in DARWIN.
- **MU (KIT):** KASCADE-Grande has accomplished its mission: The KASCADE-Grande collaboration developed and operated the cosmic-ray detector of the same name on the northern campus of KIT. The radio detection technique developed within KASCADE-Grande will now enter the next generation of projects, e.g. AugerPrime and IceCube-Gen2.
- **MU (TransFAIR FZJ/GSI):** The operation of the Cooler Synchrotron (COSY) at FZJ will be terminated after the commitments regarding FAIR (HESR, PANDA, CBM) are fulfilled during PoF IV and according to the schedule, presumably at the end of 2024.
- **MT (DESY):** The DESY–MPG collaboration project Relativistic Electron Gun for Atomic Exploration (REGAE) will be completed in 2020. The resources will be allocated to the operation of the SINBAD/ATHENA research infrastructure.
- **MT (HZDR):** The development of radiation-hard gas detectors will run out at the end of PoF III after successful prototype implementation and technology transfer to interested centers for application.
- **MT (HZDR):** The basic development of detectors, especially for medical applications, was translated to the Research Field *Health* for further development and clinical implementation.
- **MT (HZDR):** HZDR's detector laboratory for the development of detectors for the FAIR facility was closed after prototyping was completed.
- **MT (HZDR):** The department for theoretical hadron physics was restructured and reoriented to theoretical high-field physics relevant for future experiments at HIBEF in the Program MML.
- **MML (DESY):** The operation of the PITZ accelerator will be phased out in 2025. The research and development work for a future upgrade of the European XFEL will be concentrated at DESY in Hamburg.
- **MML (DESY):** A large upgrade project of the FLASH linear accelerator with a switch from pulsed operation to CW mode is no longer being considered. Instead, the CW mode will be developed as a long-term upgrade project for the European XFEL, and new concepts (e.g. seeding, advanced FEL concepts for shorter wavelengths, (sub-)femtosecond photon pulses) will be improved and implemented in the FLASH facility within the current configuration of the linear accelerator.

- **MML (HZB):** After more than 25 years of most successful user service, the BER II reactor will be taken out of operation at the end of 2019. In order to preserve the competitive instruments for the neutron scattering community, HZB is committed to transferring these instruments and the related expertise to other neutron sources in Germany, Europe, and worldwide.
- **MML (HZDR):** Research on oxygen-dispersion strengthened (ODS) steels for non-nuclear applications will be phased out until the end of PoF III.
- **MML (HZG):** Complete phase-out of the research on magnetic materials.
- **MML (FZJ):** Termination of the operation of the Neutron Spin Echo Instrument at SNS, Oak Ridge. After ten years the contract will expire at the end of PoF III.
- **MML (KIT):** Since 2015, there has been a transition of the ANKA synchrotron radiation source from a user facility (LK II) to the Karlsruhe Research Accelerator (KARA) (LK I). As part of the Karlsruhe Accelerator Technology Platform (ATP), KARA is essential for the Topic *Accelerator Research and Development* in the Program MT (MT-ARD). At KARA, KIT develops and tests novel concepts for accelerator physics and the use of synchrotron radiation.

4.2. Positioning of the Programs

The structure of the Research Field *Matter* in terms of Programs and Topics is shown in Figure 2.

Program *Matter and the Universe* (MU)

Using state-of-the-art theoretical and experimental methods, the Program MU addresses the basic correlations of the fundamental building blocks of matter and their interaction as well as the complex behavior of hadronic matter and the influence of elementary particles on the evolution of our universe. With the competences in the Helmholtz centers DESY, GSI, FZJ, IPP, and KIT and with our scientific partners all over the world, we bring together elementary particle physics, atomic and nuclear physics, astroparticle physics, astrophysics, and cosmology to handle this major task in an integral and structured way.

Our understanding of the universe is based on the standard models of particle physics and cosmology and the knowledge on how complexity originates from simpler building blocks. This framework impressively describes the elementary building blocks of matter (quarks and leptons), the forces acting between them (photons, gluons, W and Z bosons), and also the spacious structure of the universe and some of its numerous fascinating objects. A universal Higgs field and the corresponding Higgs particle seemingly give the elementary particles their mass. Our view, however, is still incomplete and partly inconsistent. To answer the many unresolved questions, the Program MU is organized around three Topics, which are thematically and methodically connected to each other.

Topic *Fundamental Particles and Forces* (MU-FPF) (DESY, KIT)

In this Topic, we explore the origin of particle masses, the quantum structure of the vacuum, and the strong and electroweak force, and we search for physics beyond the Standard Model, particularly for dark matter particles. Our focus is on the three themes i) Higgs boson and fundamental interactions, ii) Search for new particles and phenomena, and iii) Cosmology and dark matter. Prominent instruments are the ATLAS and CMS experiments at the LHC at CERN and the Belle/Belle II experiment for investigating electron-positron collisions at the Japanese High Energy Accelerator Research Organization (KEK). We develop concepts for experiments at future colliders, for experiments with neutrino radiation, and for the search for dark matter. Part of the current activities of FZJ – studying the fate of antimatter (baryo- and leptogenesis), more specifically searching for CP violation via permanent electric dipole moments (EDM) and neutrino oscillations – are also closely related to this Topic.

Topic *Cosmic Matter in the Laboratory* (MU-CML) (GSI, TransFAIR (FZJ/GSI))

In this Topic, we explore the complex and exotic forms of matter that are generated by the strong interaction (QCD) and that played a crucial role for the dynamics of the early universe and the evolution of many astrophysical objects.

Using accelerator facilities at GSI, CERN, later at FAIR, and elsewhere, we investigate the complexity of matter at all length scales, from the structure and dynamics of hadrons, emerging from quarks and gluons, to the complex and various structures of atomic nuclei and nuclear matter and their relevance for the evolution of our universe. Central open questions concern the role of spontaneous symmetry breaking in the dynamic generation of hadron masses, the possible existence of exotic and so far unknown phases of strongly interacting matter, as well as the properties of extremely short-lived isotopes and their influence on the synthesis of heavy elements in explosive processes occurring in supernovae or colliding neutron stars. A priority goal is the building and step-by-step commissioning of the FAIR accelerators and storage rings and also of the detector systems of the international collaborations APPA, CBM, NUSTAR, and PANDA (APPA is embedded in the Program MML).

Topic *Matter and Radiation from the Universe* (MU-MRU) (DESY, IPP, KIT)

In this Topic, we investigate the generation, acceleration, and propagation of high-energy particles in the cosmos, measure fundamental properties of neutrinos, and search for dark matter. The goal is a comprehensive view of the role of elementary particles in the evolution of galaxies and of the entire universe. For this purpose, we continuously advance our observatories for charged cosmic radiation, neutrinos, and gamma radiation. We particularly upgrade the Auger Observatory (AugerPrime), build up CTA, and prepare the extension of IceCube (IceCube-Gen2). We combine existing and future data of the observatories into one common multimessenger view of the universe at high energies. This view is based on a deepened understanding of the fundamental processes in magnetized plasmas of relativistic matter and in radiation fields. With the precision spectrometer KATRIN, we particularly explore the mass of neutrinos and their role as possible particles of dark matter. In future projects, we will contribute our competences to the search for dark matter.

For experimental approaches, we often need large-scale and extremely sophisticated research infrastructures, for example particle accelerators and detectors, telescopes, extended detector fields, or underground laboratories. Theory and experiment are always closely intertwined, e.g. in the comparison of theories with precision measurements and in the search for novel phenomena. The extension of experimental possibilities to higher energies, to extremely rare processes, and to very complex systems of matter is absolutely essential. Therefore, we closely cooperate with the Programs MML and MT.

LK II facilities

Ion Facilities: Investigation of matter with ions at the research infrastructures of GSI/FAIR: The LK II facilities of GSI for the Program MU (LK II GSI-MU) comprise: UNILAC and SIS18 together with the fragment separator (FRS) and the nuclear and hadron physics experiment served by the GSI accelerators, as well as the Green IT Cube for data analysis and storage. In the course of LK II operation, the implementation of novel FAIR instrumentation of NUSTAR, CBM, and PANDA for user experiments at UNILAC and at SIS18 will be pursued with high priority.

Data Centers: Our experiments produce an enormous amount of data which are processed in globally networked infrastructures (dedicated large-scale computer centers, including Green IT Cube which is currently being set up, and Tier-1 GridKA and also Tier-2 centers). We must develop new ways to enable fast and efficient data analysis. An important role also plays the development of complex algorithms which are to generate new knowledge from these data.

Program *Matter and Technologies* (MT)

Accelerators, detectors, and data are a basis for experimental research in the Research Field *Matter*, and they define the three central Topics of the Program MT. Through intensive and coordinated cooperation between the centers participating in MT and with other Programs of the Research Field *Matter*, the centers DESY, FZJ, GSI, HZB, HZDR, HZG, and KIT are laying the foundation for speeding up and optimally exploiting technological progress. This procedure has attracted interest and been imitated worldwide. In the new funding period, we will bundle the efforts in the field of data

(data taking, recording, and processing) in the new Topic *Data Management and Analysis* (MT-DMA). This Topic and the remaining part of MT are closely networked with the two other Programs of the Research Field *Matter*.

Topic *Accelerator Research and Development* (MT-ARD) (DESY, FZJ, GSI, HZB, HZDR, KIT, TransFAIR (FZJ/GSI))

In this Topic, we will develop concepts and methods in the next years to extend the possibilities of conventional accelerator systems beyond existing limits. We will optimize the achievable beam parameters with regard to particle density, pulse length, intensity, brilliance, and beam output in order to exploit so far inaccessible operating ranges. We will specifically expand activities on superconducting CW accelerators and extremely brilliant particle sources, advanced concepts for beam control, dynamics, and diagnosis, as well as the development of new methods and prototypes. Particular attention will be devoted to the development of novel plasma accelerator technologies, which will allow structures that are orders of magnitude more compact than what is possible today with conventional accelerators. The goal of the Topic is to lay the foundations for user facilities that could revolutionize our field and to move the field closer to applications.

Essential for this work are test facilities, particularly at ELBE, FLASHForward, FLUTE, bERLinPro, SupraLab, and the Accelerator Technology Platform (ATP). A central project is ATHENA, which links beacon projects for plasma acceleration of electron and hadron radiation with a distributed infrastructure.

Topic *Detector Technologies and Systems* (MT-DTS) (DESY, GSI, KIT, TransFAIR (FZJ/GSI))

The development of highly granular, pixelated detector systems has a great potential. The main challenge will be to keep pace with developments with regard to readout and detector integration. Therefore, we will set a focus on the development of intelligent sensors and detector modules, in which part of the data processing is already carried out in the detector. Nevertheless, data transfer is still a challenging task. Here, a major opportunity will be the intensive development of mixed optical and electronic systems.

We also have identified important applications for other technologies, such as semiconductor detectors. Gas-filled detectors, for example, are a cost-efficient and flexible way to instrument large volumes. Here, we approach new concepts to combine high rates and high accuracies.

More strongly than hitherto, we will focus on the development and operation of cryogenic detectors. These systems have a perfect energy resolution and are unrivalled for numerous applications that require an extremely low noise level.

For the development of modern detectors, test facilities are essential. The DESY Test Beam Facility therefore plays an important role.

We seek to exploit the considerable synergy potential in an even closer cooperation among the various centers. In order to facilitate this, we have developed the concept of a Distributed Detector Laboratory (DDL). In the DDL, we want to pool competences within the Helmholtz Association. A close integration of universities and other research organizations into this structure is one of our key concerns.

Topic *Data Management and Analysis* (MT-DMA) (DESY, FZJ, GSI, HZB, HZDR, HZG)

With this new Topic, we will meet the main challenges in handling, processing, and analyzing large amounts of data of unprecedented complexity at high rates, with the aim to support expert scientists in their research. On the one hand, we will develop the environment that the Research Field *Matter* must provide to handle data at extreme scales, and we will create modular, reusable, and open solutions for platforms that allow scientists from the diverse communities in the Research Field to actually understand and work with these data. On the other hand, we will bundle the methods and competences developed by expert scientists in these fields to provide innovative solutions, which originated from specific applications, to a wide range of users. We will take up the advancement of the rather generic concepts that are discussed in the new Research Field *Information*, and we will apply and adapt them to meet the concrete demands within the Research Field *Matter*. Conversely, we will develop application-inspired concepts towards open, reusable, and modular solutions to serve an ever-growing number of application needs. In this context, scientists in their role as co-designers and co-developers will play a significant role.

Within the new Topic MT-DMA, we will cooperate closely with scientists from all Programs of the Research Field *Matter*. The new Topic will encompass the treatment of data management and fast data-taking with full integration of the users as well as the development of advanced digital methods for data analysis and modeling with a special focus on new technologies, such as many-core computing, near-data computing, machine learning, artificial intelligence, and quantum computing, and the digital transformation of experiments and machines.

The challenge of handling and analyzing large amounts of highly complex data that are being produced at ever-increasing rates is a common across Research Fields. The new Topic MT-DMA is also designed as a future docking point for new cooperation structures between the Research Field *Matter* and the new Research Field *Information* (see Chapter 5.1 and 5.3) and the Helmholtz Incubator process. The Topic MT-DMA creates the necessary links to the research groups within *Matter*, thus enabling a transfer of concepts, methods, and solutions between the Research Field and the Helmholtz Association as a whole.

The Topics within MT cooperate closely on many levels. MT-ARD, MT-DTS, and MT-DMA are closely linked e.g. through the development of advanced accelerator concepts, powerful control systems, detectors for beam diagnostics, and powerful readout, data analysis, and management systems.

LK II facilities

IDAF: The enormous amount of data produced by experiments from particle physics, astroparticle physics, research with photons, and by simulations is processed in globally networked infrastructures. The Interdisciplinary Data and Analysis Facility (IDAF), hosted by the Program MT and designed for all the communities of the Research Field *Matter*, encompasses the Worldwide LHC Computing Grid (WLCG) Tier-2 center at DESY, but will cover a large spectrum of applications from all areas of *Matter*.

Program *From Matter to Materials and Life* (MML)

In the Program MML, we explore the detailed structure and the chemical, magnetic, and electronic properties of matter and materials, as well as (bio-)chemical, catalytic, and electronic processes at all relevant length and time scales, through the targeted use of the analytical potential of the large-scale facilities belonging to the Research Field. In the focus are complex material structures, materials under extreme conditions, as well as quantum and nanostructures and biological structures. The research program ranges from fundamental questions of condensed matter to application-oriented research projects in materials analysis for the development of new technologies up to cooperation projects with industry (see Chapter 4.5).

We expect completely novel experimental possibilities and revolutionary new insights from the experimental stations of the European XFEL X-ray laser, which should be in routine operation by the beginning of the next funding period.

The Program MML includes the LK II user operation of the large-scale facilities, in which all the organizations of the science system, particularly universities, are participating. The stable operation, the professional maintenance on site, and the dedicated measurement setups allow the analytics to be exploited for various scientific disciplines and for a broad national and international user community.

Compared to PoF III, we have reorganized the structure of the Program so as to be able to cope with the future challenges as effectively as possible: The PoF III Topic *In-House Research on the Structure, Dynamics, and Function of Matter*, which consists of five research themes, will be replaced by three new Topics, which are described in the following.

Topic *Matter – Dynamics, Mechanisms and Control* (MML-Matter) (DESY, GSI, HZB, HZDR)

In this Topic, the focus is on fundamental aspects of the structure and dynamics of complex matter. By elucidating these, we want to gain a deeper understanding of the mechanisms underlying the properties of matter and mainly use this knowledge to exercise a targeted control of these properties on a microscopic level and on ultrashort time scales. In this context, we will for example investigate the behavior of matter in electromagnetic fields that are so strong that normal approximation methods fail. Moreover, not easily accessible states of matter and dynamic processes, as they occur inside of planets and stars or in the vicinity of black holes, will be a subject of our research. Another central challenge we will face is the observation and manipulation of molecular reaction paths in real time on the atomic level. Eventually, we will extend the control of microscopic dynamics to electronic processes. This Topic is characterized by a very close and fruitful interaction of experiment and theory.

Topic *Materials – Quantum, Complex and Functional Materials* (MML-Materials) (DESY, FZJ, GSI, HZB, HZDR, HZG, KIT)

In this Topic – with the help of our large-scale facilities – we study the fundamental processes in condensed matter in order to understand and control them, and with the aim to design functional materials for novel components and active substances. This includes the investigation of the static and dynamic properties of complex quantum materials under extreme conditions, as they are provided by our research infrastructures, to find emergent properties to be used in future applications. We will carry out time- and site-resolved studies on nanomaterials to optimize the functionality in a rational way. With the *in situ* and *operando* studies of complex physical and chemical procedures in functional materials, we will gain a deeper understanding of the underlying processes, which is of direct relevance for the application of these materials.

Topic *Life Sciences – Building Blocks of Life: Structure and Function* (MML-Life) (DESY, GSI, HZB, HZG, KIT)

This Topic aims at understanding the building blocks and processes of life, from molecules up to organisms. To this end, by developing and employing MML-specific tools and techniques, we elucidate the structure, dynamics, and function of components on various hierarchical levels. From sub-cellular down to molecular levels, research focuses on the role of water in life cycles, on components in nuclei, on proteins down to individual molecular components, and on their mediation of cellular processes. On higher hierarchic levels, we study the morphology and morphodynamics of cells, tissues, organs, up to small organisms. Combining molecular and organismal strategies, we analyze genotype–phenotype correlation and reactions to stressors and stimuli including drugs, toxins, scaffolds, radiation, and environmental factors. The gained insights enable applications in health (from radiotherapy through biomedicine to biomaterial engineering), ecology (biodiversity), bionics, and others.

LK II facilities

In the upcoming PoF IV period, the Program MML will be significantly influenced by the internationally positioned large-scale facilities European XFEL (Hamburg), FAIR (Darmstadt), and ESS (Lund). The European XFEL has taken up operation in 2017 and, within the framework of PoF IV, it is important to completely exploit the enormous potential of this facility for groundbreaking experiments. Commissioning of FAIR will start in 2025, while the start of user operation at the ESS is planned for 2023. The Helmholtz centers are centrally involved in the construction of the instrumentation.

Photon Facilities: The investigation of matter at the highly brilliant synchrotron radiation sources BESSY II and PETRA III as well as at the free-electron laser facilities FLASH and European XFEL in a very broad scope of application enables the study of matter down to atomic time and length scales. DESY is co-shareholder of the European synchrotron radiation source ESRF, which is open to all German users. With regard to the usable photon energies and the reachable time scales, the mentioned sources ideally complement each other.

Neutron Facilities: The investigation of matter with neutrons at the world’s leading sources ESS, ILL, SNS, and FRM II is open for the entire neutron scattering community, e.g. for the Jülich Centre for Neutron Science (JCNS/FZJ) and the German Engineering Materials Science Centre (GEMS/HZG). A key role is played by the Heinz Maier-Leibnitz Zentrum (MLZ), a renowned national user facility of European importance. FZJ is co-shareholder of the Institute Laue-Langevin (ILL) in Grenoble, France, which is open to all German users. FZJ and HZG contribute to the construction of ESS. In addition, the opportunities for German users at the PIK reactor in Russia need to be exploited.

Ion Facilities: The investigation of matter with ions is carried out at the complementary research infrastructures of HZDR and GSI/FAIR. The HZDR operates the Ion Beam Center (IBC) for application in materials research and resource analytics. At GSI, the LK II facilities for MML (LK II GSI-MML) comprise: the ion trapping and storage ring facilities HITRAP, CRYRING, and ESR, the high-power laser PHELIX, experimental areas at UNILAC and SIS18 for atomic physics, laser- and ion-beam-driven plasma physics, proton radiography, materials research, and radiation biophysics including space research and an ion beam therapy system for pilot studies of new therapy modalities. In the course of the LK II operation, the implementation of novel FAIR instrumentation of APPA for user experiments will be pursued with high priority.

High-Field Facilities: These facilities enable the investigation of matter in highest electromagnetic fields, as available in the form of ultrahigh magnetic fields at the Dresden High Magnetic Field Laboratory (HLD) and through high-intensity photon pulses at accelerator-based infrared and terahertz sources (ELBE) and the high-power laser systems DRACO and PENELOPE (HZDR), PHELIX (GSI, associated), and at HIBEF, coupled with brilliant X-rays at the European XFEL.

4.3. Research infrastructures and roadmaps

As the operation and development of its large-scale facilities is mission-critical for the Research Field *Matter*, the national research infrastructure roadmap process is an important instrument for the Research Field to fulfill its long-term strategic planning.

The European XFEL X-ray laser has started operation in summer 2017. In 2020, we expect user operation to be well established. The Helmholtz Association, with its Helmholtz International Beamline (HIB) including the three experimental facilities HIBEF, SFX, and hRIXS – which are being built and operated under the leadership of DESY, HZB, and HZDR – is markedly participating in the use of this new large-scale facility.

In the PoF IV funding period, the BESSY VSR technology will be employed in BESSY II and TDRs will be worked out for the upgrade projects PETRA IV, BESSY III, DALI, and FLASH 2020. These upgrade activities will go along with a national roadmap process, which will be linked to the European roadmap process organized by LEAPS.

The Research Field worked out a national neutron roadmap in 2014, which was updated in 2017 and 2019. The LENS initiative will link the national strategy to the European strategies. The start of user operation at the ESS in 2023 will offer outstanding opportunities for all users in Germany. The development of compact accelerator-driven neutron sources at FZJ aims at broadening and securing the access to neutrons for research with neutrons.

FAIR in Darmstadt is scheduled to deliver first beam in 2025 and to take up operation gradually. FAIR is the flagship facility of European hadron and nuclear physics for the next decades. Moreover, FAIR will open up new and unique experimental opportunities for other research disciplines, such as atomic physics, plasma physics, and materials research, as well as biophysical radiation research, ion beam therapy, and space radiation research in close collaboration with ESA.

The next update of the CERN strategy will be ongoing during 2019/2020. The European strategy for astroparticle physics from 2010, coordinated by APPEC, was updated in 2017. In particle and astroparticle physics, the paramount projects are the detector upgrades for the high-luminosity phase of the LHC (HL-LHC) and the construction of the international CTA observatory.

The Belle II experiment in Japan commenced operation in 2018 and will proceed to collect data throughout PoF IV. The KATRIN experiment has obtained first data in a pilot run in 2019; after five years a unique data set will be available to assess the neutrino mass scale at a sensitivity level of 0.2 eV. The Pierre Auger Observatory will use the current AugerPrime upgrade for mass determination and the search for cosmic-ray sources until at least 2025. The capacities and operation concepts of the data and computer centers Tier-1 GridKa in Karlsruhe and Tier-2 NAF in Hamburg and Darmstadt must be further developed to meet the requirements resulting from international data sources, in particular from the HL-LHC. At the same time, these facilities will be kept fit for the future to cope with the rapidly advancing digital information processing.

4.4. Strategies of cooperation

The centers of the Research Field *Matter* cooperate closely with German universities and other national and international partners. Thus, several centers participate in already running strategic investments, such as the LHC upgrade, the Helmholtz Data Federation, the distributed infrastructure ATHENA, and the proposed distributed infrastructure DDL, including university groups as partners. Cooperation with universities is mostly carried out within scientific collaborations and user operation, as well as by joint appointments of leading scientists. An important instrument is the BMBF collaborative research (ErUM-Pro), which allows university groups to contribute to research and to the portfolio of instrumentation at research infrastructures.

Networking with universities and other partners from Germany and abroad was significantly expanded through many different collaborations in the past years, for example the Helmholtz Institutes in Jena and Mainz, and also through strategic cooperation agreements and projects with selected universities, partly accompanied by excellence programs of the states. These networking and cooperation activities must be further strengthened in the coming years. A main focus lays on the German federal excellence strategy, in which all centers of the Research Field will act as partners of the respective excellence universities.

The advanced large-scale user facilities of the Research Field *Matter* play a very important role as they are interdisciplinary platforms which attract every year many thousands of researchers from all over the world to closely work together with Helmholtz research groups. Together with the ambitious Programs, they play an essential role as talent factories for junior scientists in state-of-the-art technology- and science-oriented surroundings, but also for attracting and training of engaged and motivated technicians and engineers

4.5. Transfer of knowledge and technology

The core mission of the Research Field *Matter* is the exploration of matter and the ownership for the development, construction, and operation of large-scale research and user facilities, which themselves offer great potential for innovation and for closing chains of innovation in an industrial context. For the Research Field *Matter*, technology transfer is thus anchored centrally in the core mission.

Innovation and technology transfer is strongly embedded in the individual center strategies. Each center covers both the legal tasks in this area and the strategic aspects as part of the scientific program. The Research Field as a consortium of eight centers can make a substantial contribution to strengthening the decentralized innovation activities. Due to the complexity of current and future technologies within the Research Field, it is crucial that a continuous exchange of experiences takes place between the centers. For this purpose, new exchange formats will be developed further, so that all the centers can benefit from the experience of the others and share market-driven information for a professional transfer. In addition, a platform is to be created to partially organize sales and marketing activities together. Working together in this field will strengthen the portfolio of the individual centers, making them more attractive for potential industrial partners. In addition, joining forces in organizing appearances at large trade fairs or conferences will reduce risks and costs.

The Research Field *Matter* can act as a network for better meeting industrial needs. Thanks to the complementarity of methods and research priorities, the Research Field as one body can formulate attractive and highly competitive packages offers to industry. This will strongly support the high-tech strategy of the German federal government. Innovation will become more prominent in the Research Field *Matter*, addressing particularly materials design and molecular biology.

The centers of the Research Field will create suitable structures in order to anchor the cooperation with industry including

- the targeted opening of research infrastructures for industrial users and the promotion of a corresponding business-oriented culture in the centers,
- the establishment of strategic partnerships with industry in order to coordinate goals and research needs at an early stage, and
- the creation of suitable structures in the centers in order to anchor cooperation with industry organizationally, as by appointing chief technology officers and/or innovation service centers.

Another core element of the mission of the Research Field *Matter* is the transfer of knowledge to society, creating a broader acceptance for fundamental research. For this purpose, our research centers have implemented special units, which manage the knowledge transfer processes locally and organize various activities on the regional levels. These include e.g. public days, guided tours of the research centers and participation in local public dialogues. In addition, scientists of the Research Field *Matter* are involved in information services for experts, consultations for society or politics, and in platforms and networks. Other important components of knowledge transfer are student laboratories and teacher trainings, which are becoming increasingly popular and contribute to the education of tomorrow's generations. A successful format of knowledge transfer in *Matter* are public lectures at somewhat unusual locations, as in bars and pubs.

Representatives from all centers of the Research Field participate in the Helmholtz-wide working group *Knowledge Transfer*, which was set up in 2018. Together, they are developing further activities for a strong and regular knowledge transfer in line with the strategy of the Helmholtz Association.

4.6. Diversity and talent management at the level of the Research Field

The scientific success of the Research Field depends critically on the recruitment and promotion of excellent scientific, technical, and administrative personnel, as well as on a non-discriminatory working environment that fosters a highly diverse human resources management culture. In the headhunting of key experts and young talents, the Research Field *Matter* is in strong competition with industry, universities, and other research institutions. Talent management, in turn, requires special attention.

In order to promote the recruitment, training, and retention of talented employees and young experts, the Research Field *Matter* offers personnel exchange with partners from science and industry on a national and international level. In this context, access to the large-scale research infrastructures of the Research Field *Matter* is an important pillar, as they provide an interdisciplinary and excellent working environment for internationally competitive research that attracts the best minds.

We emphasize our strategic cooperation between the centers and their university partners as a most successful instrument for attracting young brains. Excellent examples are the many joint professorships and the various joint graduate schools, career centers, and international offices that benefit from Helmholtz funding. A particular current highlight is the cooperation between the Research Field *Matter* and the universities within the German excellence strategy, which should in future attract even more brilliant young students into the research environment of the Research Field.

A future focus of the Research Field will be on the recruitment of experts in the data and simulation sciences. Existing structures will be revised, and a comprehensive qualification program and new career paths will be established as part of PoF IV for experts from computer science, mathematics, and the data and simulation sciences. The newly established data science graduate schools are an important pillar of this future strategy.

Diversity and gender equality have been and will remain a core business of the research centers. The Research Field is determined that its centers should be places where people work together peacefully towards a common goal, irrespective of nationality, gender, skin color, religion, and private life style. Gender equity and equality will remain a guiding principle in all fields of action, by placing a strong emphasis on the recruitment of excellent female scientists, in particular at the W2 and W3 level (promoted by the Helmholtz Initiative and Networking Fund). Appropriate structures, such as flexible childcare services, specific programs and networks for female researchers, and dual career opportunities will be continuously expanded. Specific training programs are available to young women researchers, offering a combination of (leadership) training, networking, and mentoring. Several centers have introduced voluntary quotas aiming to increase the proportion of women at all career stages. Program-specific activities will be explained in the proposals of the Programs MU, MT, and MML.

5. CROSS-CUTTING ACTIVITIES

The cooperation with other Research Fields will be further intensified. Connections already exist in multiple ways – through people, common projects, or shared methods. Several activities have been identified that request even closer cooperation across Research Fields. This chapter describes the five most important Cross-Cutting Activities (CCA): (1) *Information and Data Management*, (2) *Materials Research*, (3) *Quantum Technologies*, (4) *Structural Biology and Biological Processes*, and (5) *Radiation Research a*s well as the Matter Forum to initiate interdisciplinary pilot projects (see Chapter 5.6).

5.1. Information and Data Management

Cooperating Research Fields: *Information* and *Matter*

As one of the major megatrends, digitalization is impacting and reinventing all areas of life. It is of outstanding importance for the competitiveness of Germany as a science and business location. The Helmholtz Association develops a common digitalization strategy that initiates viable solutions in all the Research Fields in order to meet this major social challenge. Within this strategy, the Helmholtz Association will assume a pioneering role in the consistent transfer of concepts, methods, and solutions to society, science, and industry, especially regarding the Helmholtz Association's use of information processing and information technologies as well as open science.

The Helmholtz Association is shaping the digital transformation both on the national and international level. With a unique combination of knowledge- and technology-oriented research and development, the Association contributes to powerful, energy-efficient, and secure information technologies. Through the use of advanced digital methods, completely new knowledge and organization processes are made possible in all the Research Fields as described in the Helmholtz digitalization strategy. In this way, Helmholtz also offers a highly attractive environment for data experts.

This issue is of great importance in the Research Field *Matter*, as witnessed by the creation of the new Topic MT-DMA. The collection, handling, storage, access, and use of the huge data sets that are characteristic for research in *Matter* are areas where a close cooperation with the Research Field *Information* is of great mutual interest. In fact, handling the enormous challenges with which the Research Field *Matter* is faced in this area requires close cooperation, the right infrastructure, and in many ways fundamentally new ideas and concepts.

We see great potential for a close cooperation with the Research Field *Information* in this area. The concrete problems and questions that arise within *Matter* can profit greatly from the more fundamental approach followed in *Information*, while *Information* can use the real-life problems in *Matter* to test and develop their solutions. We have already identified two initial areas where we see the greatest potential for cooperation:

- **Exascale algorithms and workflows for plasma simulations**. Research into novel plasma-based particle acceleration concepts and fusion energy research are high-priority research directions. Because of the multiscale, non-linear dynamics that dominate in plasma physics, modeling these processes requires the use of exascale compute power. The scalability and performance of central algorithms e.g. in kinetic plasma simulations to exascale dimensions must be addressed. Due to the growing complexity of these simulations, their integration into scalable workflows is of greatest importance. Participants are DESY, FZJ, GSI, HZDR, IPP, and KIT.
- **Quantum simulations of complex quantum systems.** Quantum computing and annealing are new and potentially breakthrough approaches that may help to speed up calculations significantly compared to classical computing approaches. We will investigate the use of quantum algorithms for analyzing complex quantum systems in high energy, high energy density and warm dense matter physics. Participants are DESY, FZJ, and HZDR.

Work within this CCA will build on past and existing successful projects and collaborations between the two Research Fields *Matter* and *Information*, such as the Large Scale Data Management, the Helmholtz Data Federation, and others. These activities are embedded in an intense collaboration of partners on a national and European level.

5.2. Materials Research

Cooperating Research Fields: *Aeronautics, Space and Transport, Energy, Health, Information,* and *Matter*

Modern Materials Research has become a highly cross-disciplinary effort in order to cope with the challenges to rationally design novel multifunctional materials made to measure. They are critical for all future technologies ranging from renewable energy systems and future information technologies to biomedical materials.

In this context, a joint effort of the Research Fields *Information, Matter,* and *Energy* on materials research has been initiated with contributions from the Research Fields *Aeronautics, Space and Transport* as well as *Health*. Together, the Research Fields will develop a comprehensive Helmholtz materials research strategy that systematically builds on their complementary competencies and unique selling points in relation to the Helmholtz mission and combines the special scientific possibilities of the centers with application perspectives. The strategy will present the definition/description of interfaces in the sense of synergies between the individual Research Fields. In order to achieve a quality leap in the development of new materials, so-called "focus areas" across the Research Fields will be established and expanded. These are highly internationally visible thematic bridges, e.g. information-based materials design, materials imaging, and application-driven themes such as quantum materials or energy storage. The strategy will be finalized taking into account the results of the strategic evaluation and subsequently implemented. As a result, the Helmholtz Association will reach an outstanding position in materials research in the national and international scientific system.

The main pillars of materials research within the Helmholtz Association are:

- The special competencies in the development, construction, operation, and use of large research infrastructures for issues from different disciplines to characterize materials
- Development of new systemic approaches in materials research based on the possibilities of digital transformation (e.g. modeling/simulation, parallel consideration of real and "digital twin"), in particular to shorten the development cycles in materials development and to realize a faster transfer to industrial application
- Application-oriented materials research based on specific problems from the various Research Fields.

The individual Research Fields contribute their specific expertise, as shown in Figure 3.

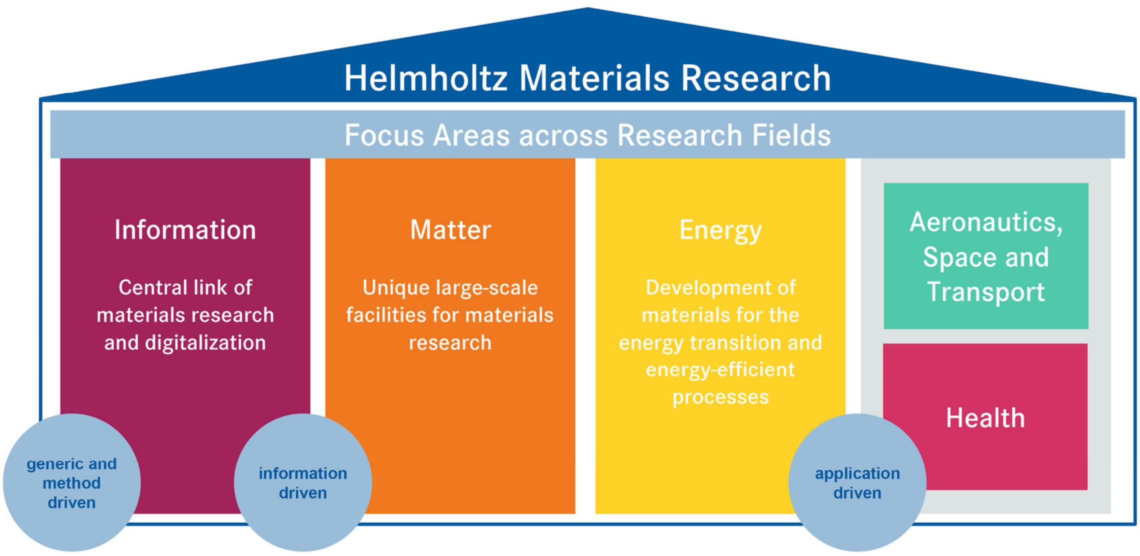

Figure 3: Materials research in the Helmholtz Association – complementary competencies of the Research Fields

The Research Field *Matter* develops, constructs, and operates unique research infrastructures, such as photon and particle sources, mainly as user facilities. These include BESSY II, PETRA III, KARA, FLASH, the European XFEL, JCNS, GEMS, MLZ, IBC, GSI/FAIR, HLD, and ELBE. With its large-scale facilities, the Research Field *Matter* contributes to materials research in the Helmholtz Association through interdisciplinary questions on the characterization, modification, and synthesis of materials. Work is aimed in particular at obtaining in-depth microscopic understanding of matter, materials, and biological systems. Furthermore, at its large-scale facilities, the Research Field *Matter* performs application-oriented materials research based on specific problems from the other Research Fields.

5.3. Quantum Technologies

Cooperating Research Fields: *Aeronautics, Space and Transport*, *Information*, and *Matter*

The Helmholtz Association will contribute extensively to the framework program on quantum technologies announced by the German federal government in September 2018 as well as to the European Quantum Technologies Flagship initiative. A strategy paper on quantum technologies has been elaborated by a working group composed of representatives of all the different Helmholtz centers involved, which form a cross-cutting network comprising not only discovery- and technology-oriented research but also research infrastructures and large-scale facilities.

As highlighted in this strategy paper, current research within the Helmholtz Association spans a vast array of subjects in the areas of computing, communication, and sensing: from the understanding of fundamental quantum phenomena to the development and design of components, prototypes, and fully functional systems addressing real industrial use cases. These subjects fit in three Research Fields*: Information, Matter,* and *Aeronautics, Space and Transport*.

One of the challenges for developing quantum technologies is that it is so far not clear which of the currently most advanced qubit platforms investigated in the Research Field *Information* is most suitable for building a quantum computer. There is also still much room for improvement, either incremental or disruptive. The latter is expected to come from new concepts emerging from research on quantum materials, i.e. systems with unique quantum-mechanical properties characterized by concepts of topology and entanglement.

Research on quantum materials is aimed at developing a suitable material base for quantum technology: A prerequisite for exploring the fundamentals of quantum systems at the atomic and molecular scale and tailoring their quantum-mechanical properties with atomic precision is to understand the dynamics of novel quantum states arising at interfaces, in exotic materials, or in highly excited systems, and to find solutions for the decoherence mechanisms in quantum systems. It is also important to study the coupling between solid-state qubits and photons for the coherent exchange of quantum information between matter and light.

For research on quantum materials, the use of high-end large-scale facilities as available in the centers of the Research Field *Matter* is a particularly strong asset, both for the fundamental research to be conducted and for the development of devices. The available research infrastructures enable the study of the properties of quantum materials through most advanced spectroscopy and imaging methods, from next-generation electron microscopy to neutron, laser, high-field, and synchrotron radiation sources, allowing electronic states to be investigated with respect to all quantum numbers at ultimate time and length scales.

5.4. Structural Biology and Biological Processes

Cooperating Research Fields: *Health*, *Information*, and *Matter*

Despite enormous progress made in our understanding of the structure and function of biological macromolecules and macromolecular complexes, we are still far away from a complete understanding of larger biological systems such as a cell or even an organ at the molecular level. However, this information is required to understand molecular mechanisms in physiological and pathological pathways and develop novel therapies to cure human diseases. Major progress in this field is dependent on large improvements in the capabilities of the applied analytical tools, which need to span the relevant resolution range from micrometers to the atomic level and at biologically relevant time scales.

In order to help to address these challenging goals, the CCA *Structural Biology and Biological Processes* brings together expertise in biological and medical research of the Research Field *Health* with the methods, expertise, and large-scale facilities of the Research Field *Matter*. These facilities – synchrotron radiation, FEL, and neutron sources – provide powerful probes for determining the three-dimensional structure and dynamics of biomolecules or biomolecular complexes, which is instrumental for understanding biological functions. The Research Field *Health* complements these infrastructures with high-end NMR facilities, including 1.2 GHz and dynamic nuclear polarization instruments, to provide unique information about the dynamics and interactions of biomolecules in solution and in heterogeneous phases. The techniques offered by these infrastructures allow structural investigations of complex biological systems at spatial scales ranging from the arrangements of atoms by crystallography methods to cellular structures of sizes from 10 nm to micrometers by X-ray microscopy and tomography methods, closing the gap to optical microscopy. Dramatic progress in cryo-electron microscopy during the last decade has closed the gap between the atomic resolution obtained from crystal structures and the size of large macromolecular assemblies in the regime of several 10 to 100 nm. NMR methods provide unique information for studying the dynamics of biological macromolecules in solution and in heterogeneous phases, such as disease-linked amyloid fibrils, yielding essential information for understanding their biological function. Synchrotron and neutron small-angle scattering techniques provide complementary information on the dynamics.

An additional boost for understanding the dynamics of biological molecules is expected from the newly developed serial crystallography techniques that are being carried out at synchrotrons and X-ray FELs. The use of micrometer-sized or smaller crystals is not only an advantage when the growth of larger crystals is difficult or impossible. It also enables time-resolved experiments for dynamics and functional studies using pump–probe and mixing techniques from the femtosecond to the several microsecond regime, respectively.

For the PoF IV period, an even stronger combination of the various radiation-based techniques in connection with cryo-electron microscopy experiments will be pursued to take full advantage of the now available coverage of the entire resolution range required to investigate biological systems. Functional studies at the atomic level will experience a dramatic push by the femtosecond time-resolved capabilities provided by FEL sources. Furthermore, new methods to be developed for localizing functionalized nanoparticles in larger tissue samples or organs will open new avenues for medical imaging.

The CCA *Structural Biology and Biological Processes* organizes annual meetings to exploit unique opportunities for integrative structural biology and workshops to train young scientists in these interdisciplinary approaches. Furthermore, by playing a leading role in national structural biology initiatives, the CCA contributes to science policy and decision-making in Germany and Europe, thereby enhancing the national and international visibility and competitiveness of the Helmholtz centers. For the PoF IV period, we will (i) continue our networking (annual meetings) and training activities (Helmholtz workshops in integrative structural biology), (ii) develop novel integrative structural biology approaches, including NMR, X-ray crystallography, and cryo-electron microscopy, and (iii) advance and strengthen computational methods, including artificial-intelligence/machine-learning-based approaches in structural biology and structure-based drug discovery.

Present collaborations between the Research Fields *Health* and *Matter* include the joint operation of the structural biology beamline P11 at PETRA III and the innovation pool project SX-FragS, where structural biologists from both Research Fields collaborate on innovation in structure-based drug discovery. In the Centre for Structural Systems Biology (CSSB), a collaboration of nine institutions in the field of infection research on the DESY campus, HZI, FZJ, and DESY each contribute a W2/3-level research group to this collaborative effort.

5.5. Radiation Research

Cooperating Research Fields: *Aeronautics, Space and Transport, Energy, Health,* and *Matter*

This CCA aims at understanding the impact of ionizing radiation on biological systems at various scales, capitalizing on the competences in radiation research from different Research Fields. The activity includes radioecology, radiation protection, dosimetry, radiobiology, and radiotherapy. Radiation is indeed a double-edged sword. On the one hand, research on high dose effects in tumors and normal tissues is highly necessary to improve cancer treatment. On the other hand, investigation of long-term effects of exposure (external or internal) to low dose and low dose rate radiation is relevant for the prolonged intermediate disposal of nuclear waste in the context of the phase-out of German nuclear power plants (7th Federal Energy Research Program). The CCA bundles the expertise of different centers in various Research Fields to enable knowledge-based societal decisions in both radiation medicine and radiation protection. Radiation Research was already established in PoF III, involving the Research Fields *Health and Energy*. The initiative led to a number of collaborative research activities and to the identification of potential synergies. In PoF IV, we aim to extend the network to the Research Fields *Energy, Health,* and *Matter*, with contributions from *Aeronautics, Space and Transport,* and *Information*. The goal is to strengthen the links among the various Research Fields and to exploit the different expertise in the Helmholtz Association in order to address key problems in radiation research.

A major issue is the accurate determination of exposures in different radiation environments (workplaces, medical application, households) and the development of solutions to keep the doses as low as reasonably achievable (ALARA principle). Additionally, the development of strategies to minimize potential risks from the decommissioning and long-term deposition of nuclear waste is essential, including quantification of the effects of secondary radiation such as neutrons. Here, dose estimations after radiation exposures are critical. At present, they are performed using standard techniques and reference values. To account for physiological variation, future efficient radiation protection concepts need to be personalized and include microdosimetry. A major challenge in radioecology and radiation biology is the proof and ideally the live-cell quantification of the effects of low radiation doses including incorporated radionuclides (RNs). Moreover, RN entry into the food chain is a prime research focus. Novel combinations of calorimetry, biochemistry, RN isotope selection, and gene expression analysis are currently under development to distinguish actual radiation effects from purely chemical radionuclide toxicity. Radiation protection extends to air travel and space exploration, and in-flight measurements can be matched by space radiation simulations at the large Helmholtz particle accelerators.

In radiation therapy, the competences and large infrastructures in the Research Field *Matter* will support the biomedical expertise in the Research Field *Health* in order to optimize cancer treatment. The centers have an outstanding tradition in the field of particle therapy, where patients are treated with protons or carbon ions. The CCA will focus on optimizing current clinical procedures, both in physics (in particular with new detectors for the reduction of range uncertainty and for organ motion management during the delivery of ion beams by raster scanning) and in biology (with studies on biomarkers, radiogenomics, and the combination of particles with other treatments, especially immunotherapy). In addition to these translational research themes, the CCA will explore future breakthroughs in radiotherapy with novel, unique infrastructures, in particular FAIR (which allows the production of ion beams with unprecedented high intensity) and laser-driven particle accelerators (which have the potential to reduce the size and cost of particle therapy centers).

5.6. Matter Forum for interdisciplinary pilot projects

Overall, cooperation across the Programs of the Research Field *Matter* or with other Research Fields will be further intensified, as we see potential here for cross-cutting initiatives and projects leading to new discoveries and technologies. Therefore, the Research Field has decided to implement the Matter Forum, which in future will initiate, coordinate, and fund activities across Programs. The Matter Forum will be a new platform to initiate and enable projects in research, technology development, and innovation, as well as in talent management and communication. For this purpose, each research center will reserve 1% of its LK I budget of the Research Field *Matter* to initiate joint activities. The Matter Forum will be run by the three Program spokespersons, who will organize annual Marketplaces of Ideas and submit emerging proposals for new initiatives to the Management Board of the Research Field *Matter*. The Research Field considers the Matter Forum also as a tool to strengthen the dynamic development of the field and to react in a non-bureaucratic way to new ideas, particularly of our young scientists.

6. PROFILES OF THE HELMHOLTZ CENTERS

6.1. Deutsches Elektronen-Synchrotron (DESY)

The DESY research center with about 2,600 employees is one of the world's leading laboratories for the exploration of matter. It has various important roles in the German science system: DESY is a strategic partner of the university of excellence Universität Hamburg and is involved in three of its four clusters of excellence, and DESY is a national anchor in many international large-scale collaborations. The central core competence of the research center lies in mastering all scientific, technical, and organizational aspects of large accelerator facilities.

Research at DESY is structured into four areas: accelerator development, photon science, particle physics, and astroparticle physics. DESY operates in two locations, Hamburg and Zeuthen near Berlin. In Hamburg, the focus of research activities is on photon science with the large-scale research facilities PETRA III, FLASH, and the European XFEL X-ray laser, on accelerator development, and on particle physics with the large-scale facilities Detector Assembly Facility (DAF) and the Tier-2 center. In Zeuthen, DESY focuses on astroparticle physics.

With its large-scale research facilities PETRA III and FLASH and its participation in the European XFEL, as well as its interdisciplinary science platforms (such as CFEL and CSSB), DESY provides unique tools and facilities for physicists, chemists, biologists, materials scientists, geophysicists, and physicians to carry out their ambitious research projects. Around 3,500 guest scientists from over 40 countries use the DESY research facilities for their experiments every year.

In particle physics, the research center works closely with CERN and the Japanese High Energy Accelerator Research Organization (KEK). Over the next few years, DESY will expand its expertise in astroparticle physics. Important projects here are the IceCube detector at the South Pole and the CTA gamma-ray observatory, which is currently being built. DESY has been awarded the contract to set up the CTA Science Data Management Centre (SDMC).

In order to achieve scientific breakthroughs, DESY relies on the pool of ideas of its scientists and in particular of its junior scientists. Thus, DESY sees a continuous challenge in recruiting highly talented scientists, enabling creative basic research, and organizing further interactive, interdisciplinary research platforms as the Wolfgang Pauli Centre (WPC) and the Centre for Molecular Water Science (CMWS).

Over the past five years, innovation and technology transfer have become an essential part of the DESY mission. The innovation strategy of the lab, under the leadership of the DESY CTO, is based on three pillars: innovation services, technology transfer, and spin-off companies.

DESY is facing major technological challenges: The technical conversion of PETRA III into a next-generation storage ring (PETRA IV project) requires new solutions in storage ring technology, new detectors and X-ray focusing optics, as well as new solutions in dealing with the exponentially growing amounts of data in future experiments. In particle and astroparticle physics, the demand for ever faster and more complex detector systems will increase. As a first measure, the DESY Tier-2 center will be upgraded into the Interdisciplinary Data and Analysis Facility (IDAF).

Over the next few years, DESY will face the challenge of devising new concepts for ultrahigh-field accelerators and applying them. With the new SINBAD infrastructure, the ATHENA project, and the appointment of Wim Leemans from the Lawrence Berkeley National Laboratory as new director of the accelerator division, the foundation for a successful development has been laid.

6.2. Forschungszentrum Jülich GmbH (FZJ)

With about 6,000 employees, including approximately 550 doctoral researchers, and a total budget of 610 million euros per year, FZJ is one of the largest institutions of the Helmholtz Association in Germany. Over the years, FZJ has been able to diversify into a multidisciplinary research center that encompasses a broad range of methodological tools and pursues a systemic scientific approach across disciplines with a strong background in natural sciences and a special focus on fundamental physics and materials engineering. Currently, research at FZJ is organized into the four Research Fields *Information*, *Energy*, *Earth and Environment*, and *Matter*.

FZJ is committed to undertaking world-class research through its excellent staff and infrastructure. Supporting young people and scientists at all stages of their careers is an integral part of the overarching talent management strategy at FZJ: introducing children and teenagers to research, developing innovative structures for vocational training, and providing early-career scientists with outstanding conditions for achieving excellence. About 1,000 doctoral researchers are supervised by one of the research institutes at FZJ. In its role as a multithematic and interdisciplinary research center, cooperation, internally as well as with regional (e.g. Jülich-Aachen Research Alliance (JARA) with university of excellence Rheinisch-Westfälische Technische Hochschule Aachen or MLZ together with HZG and Technische Universität München) and worldwide partners (e.g. ESS or ILL), is key to exploiting its potential to the fullest. FZJ aims to collaborate with excellent scientific partners as well as with leading players from industry, and its experts are involved in major national and international stakeholder groups. About 800 visiting scientists from up to 75 countries join FZJ every year.

The major strategic objective is to generate impact by use-inspired basic research as a relevant scientific contribution to solving the grand challenges facing society. The particular strength of FZJ – the provision of research infrastructures as interdisciplinary user platforms – is also reflected in the variety of scientific methods and instruments operated and developed by the center. Thus, instruments and infrastructures in Jülich comprise simulation and data management tools, supercomputers (Jülich Supercomputing Centre (JSC)), unique analytical and characterization equipment (e.g. Ernst Ruska Centre for microscopy and spectroscopy with electrons or Jülich Short-Pulsed Particle and Radiation Center (JuSPARC), a laser-driven photon and particle beam facility), imaging techniques for neuroscience and medicine, as well as nanotechnology tools and a cleanroom facility. For all research infrastructures, we have closely linked our method development to the disciplinary research to ensure a demand-driven method and technology development. In particular, the combination of know-how in high-performance computing for simulation and data sciences with analytical methods available at FZJ is unique and offers exceptional possibilities.

Concerning the activities in the Research Field *Matter*, a special focus of FZJ lies on the development of neutron scattering methods and on the Jülich Centre for Neutron Science (JCNS) user facility, which has outposts at MLZ in Garching and at powerful international neutron sources. Moreover, JCNS plays a leading role in the construction of instruments for the ESS and the development of a new generation of compact neutron sources. At the same time, Germany and Russia have signed a German–Russian roadmap with one goal being to contribute German instruments to the user platform at the PIK reactor in Gatchina. Research at JCNS focuses on correlated electron systems and nanomagnetism as well as on soft matter and biophysics. In these areas of expertise, JCNS offers support on state-of-the-art instruments with specialized sample environment and ancillary laboratory access for external users. Capacities will be specifically expanded for research into energy materials.

During PoF IV it is planned to transfer the activities of the FZJ Institut für Kernphysik (IKP) to GSI. Please refer to Chapter 6.3. for further information on TransFAIR (FZJ/GSI).

6.3. GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI)

With about 1,350 employees and a user community of more than 1,500 researchers from all over the world, GSI is the premier center for heavy-ion research in Europe. It comprises the main campus in Darmstadt (GSI-DA) with about 1,200 employees and two Helmholtz Institutes, located at the universities of Jena and Mainz, with about 150 employees. GSI and its two Helmholtz Institutes are strategically embedded in all three Programs of the Research Field *Matter*, MU, MML, and MT.

On its campus in Darmstadt, GSI provides a large LK II infrastructure of accelerators and storage rings for the production, storage, and cooling of all ion species, from protons to uranium, in virtually any charge state and up to relativistic energies of 1–2 GeV per nucleon. Together with a suite of detectors and other instrumentation, including the kilojoule/petawatt laser facility PHELIX, this infrastructure enables fundamental research in hadron, nuclear, atomic, and plasma physics, nuclear astrophysics, and applied sciences such as materials research and radiation biophysics with relevance to health applications and space science. GSI cooperates closely with the universities of Darmstadt, Frankfurt, Gießen, Heidelberg, Mainz, and Jena. The cooperation includes joint appointments for leading positions, R&D contracts to fund graduate students and postdocs for pursuing research on GSI/FAIR-related subjects, the regional cooperation network HIC for FAIR within Hessen, and the joint Helmholtz Graduate School HGS-HIRe for FAIR, which offers structured education and training for more than 300 doctoral students.

Also during PoF IV, GSI will focus on the further construction and commissioning of FAIR as an international research center adjacent to the GSI campus. GSI serves as the host lab for all FAIR experiments and is responsible for the overall coordination of the global activities within FAIR. FAIR is designed to deliver high-intensity and high-energy primary beams from protons to uranium and secondary beams including exotic nuclei far off stability and antiprotons, which can be stored and cooled for highest beam qualities. Research is conducted in four scientific pillars: APPA (Atomic Physics, Plasma Physics and Applied sciences), CBM (Compressed Baryonic Matter), NUSTAR (NUclear STructure, Astrophysics and Reactions), and PANDA (antiProton ANnihilation at DArmstadt).

The mission of the Helmholtz Institute Jena at the Friedrich-Schiller-Universität Jena is excellence in fundamental and applied research based on X-ray science, high-power lasers, and particle accelerators. It is embedded in the Programs MML and MT with strong participation in the APPA pillar of FAIR. The focus is on research at the interface of accelerators and lasers with the Friedrich-Schiller-Universität Jena, DESY, and HZDR as partners. It is also a partner of the cluster of excellence *Balance in the Microverse*. The mission of the Helmholtz Institute Mainz at the Johannes Gutenberg-Universität Mainz is excellence in hadron, nuclear, and fundamental physics, as well as accelerator and detector developments within the Programs MU and MT and the FAIR pillars PANDA and NUSTAR. Further foci are the chemistry and physics of superheavy elements and tests of fundamental symmetries with low-energy antiprotons. The Helmholtz Institute Mainz is in the cluster of excellence *PRISMA*.

It is planned to transfer the activities of the IKP (except for the theory institute IKP-3) from FZJ to GSI. The transferred IKP activities (TransFAIR FZJ/GSI) will focus on the realization of the High Energy Storage Ring (HESR) and on major components of the PANDA detector at FAIR. Moreover, they will address precision physics experiments, in particular with polarized particles. The TransFAIR FZJ/GSI activities, which are carried out in close cooperation with the universities of Aachen, Bochum, Bonn, Cologne, Düsseldorf, Mainz, and Münster, are embedded in MU and MT. The full competences of the IKP will thereby be retained within HGF.

6.4. Helmholtz-Zentrum Berlin für Materialien und Energie (HZB)

With approximately 1,200 employees and an overall budget of 165 million euros per year, HZB contributes to the Research Fields *Matter*, *Information*, and *Energy*. Research at HZB ranges from basic materials science to providing solutions to the global energy challenge, e.g. for energy conversion and storage as well as efficient energy use. Spectroscopic methods based on soft and tender X-rays are ideally suited for HZB's research, since they provide advanced analytical techniques accessing the electronic and magnetic properties of matter. BESSY II, the synchrotron radiation source operated by HZB, is optimized for this spectral range and serves the national and international user community. Continuous facility upgrades and method developments result in novel tools for *in situ*, *in system,* and *operando* investigations of materials and processes at all relevant length and time scales. A prominent example is the Energy Materials In-Situ Laboratory (EMIL@BESSY II). The development of appropriate data management and analysis tools for these infrastructures is becoming more and more important. Accelerator research at HZB provides the basis for reliable operation and continuous improvement of BESSY II. The ongoing development of the variable pulse length storage ring scheme (BESSY VSR) will enable novel experimental capabilities for time-resolved experiments at synchrotron storage rings. HZB is identifying the science- and technology-driven requirements for a diffraction-limited future light source in the soft X-ray range (BESSY III). Highest stability enabling experiments with nanometer spatial resolution and unprecedented spectral resolution will be a key property of this next-generation facility.

HZB is firmly rooted in the Berlin–Brandenburg scientific area. Cooperation with its main strategic university partners Freie Universität Berlin, Technische Universität Berlin, and Humboldt-Universität zu Berlin, as well as Potsdam University is well established in the form of joint appointments, joint labs, and joint research groups, as well as common graduate and research schools. Within the German excellence strategy, HZB is a strategic partner of the Berlin universities in two clusters (clusters of excellence funding line) as well as in the Berlin University Alliance (universities of excellence funding line). The Physikalisch-Technische Bundesanstalt (PTB) is a longstanding strategic partner of HZB; PTB uses BESSY II as the European radiation standard and operates a dedicated metrology laboratory at BESSY II that frequently attracts industrial users. The PTB-owned Metrology Light Source (MLS) has been developed and is operated by HZB. MLS is also used by HZB for accelerator physics studies. HZB has a well-established and very close strategic partnership with the Max Planck Society (MPG), which is further intensified by a new level of collaboration in the field of catalysis and energy chemistry.

HZB recognizes the importance of talent management and career development options for all its employees. To this end, it employs programs organized at the level of the Helmholtz Association as well as HZB-specific measures, such as structured doctoral candidate education, a postdoc career office, and the implementation of organizationally independent junior groups. Since 2011, HZB is holding the “berufundfamilie” (Career and Family) certificate.

HZB is dedicated to fostering the transfer of its knowledge and technology into industry and society. HZB’s technology transfer follows two main routes. The first one is to promote the use of its infrastructures by industrial users, e.g. by setting up customized laboratories such as EMIL@BESSY II or SupraLab@HZB. The focus of the second route is to bring innovative devices and processes to the market. Here, prominent examples are the Helmholtz Innovation Lab HySPRINT, which deals with (opto)electronic materials, and the Competence Centre Thin-Film- and Nanotechnology for Photovoltaics (PVcomB). The HZB industry advisory board supports these activities and provides feedback on industry needs.

6.5. Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Helmholtz-Zentrum Dresden-Rossendorf (HZDR), founded in 1992 as a member of the Leibniz Association, became a member of the Helmholtz Association in 2011 following a positive evaluation by the German Research Council. Today, ca. 1,200 staff members are working at the center in eight institutes. HZDR strives for internationally leading positions in its core Research Fields *Energy*, *Health*, and *Matter* and aims at developing original scientific ideas in order to provide answers to today’s societal challenges. With HZDR Innovation GmbH, it holds a company that provides professional science-driven services for industry and serves as an incubator for new foundations. Strategic partnerships with the university of excellence Technische Universität Dresden, the local science network “DRESDEN concept”, as well as further regional universities and collaborations with important international partners from science and industry lay the foundation for high-level competitive research.

In the Research Field *Energy*, the scientific activities focus on energy-efficient processes, resource technologies, liquid-metal batteries, nuclear waste management, and reactor safety. In the Research Field *Health*, HZDR focuses on imaging and radiotherapy of cancer, in particular the evaluation and improvement of proton radiotherapy and the development of alternative compact high-power laser-based proton sources, closely linked to the activities in the Research Field *Matter*. The research is conducted within the joint research platform OncoRay, the National Center for Radiation Research in Oncology, and the National Center for Tumor Diseases (NCT).

In the Research Field *Matter*, the scientific activities of HZDR are mainly based on its three large-scale user facilities, the Ion Beam Center (IBC), ELBE – Center for High-Power Radiation Sources (ELBE), and the Dresden High Magnetic Field Laboratory (HLD), as well as the experimental Dresden Sodium Facility for Dynamo and Thermohydraulic Studies (DRESDYN). The center’s activities concentrate on research on extreme states of matter and quantum-condensed matter within the Program MML and on accelerator research and development as well as data management and analysis in the Program MT. Moreover, HZDR operates its user facilities to provide access for researchers from physics, materials science, chemistry, resource technologies, and the life sciences. IBC is continually being upgraded with major focus on low-energy ions for 2D material modification and analysis as well as on capabilities in accelerator mass spectrometry (AMS). ELBE recently received two additional secondary radiation sources, the THz facility TELBE and the positron source pELBE. Moreover, HZDR, which is internationally recognized as one of the leading players in this field, presently also operates Germany's most powerful laser at the ELBE facility. HLD provides the highest magnetic fields over various time ranges and a broad portfolio of experimental setups. DRESDYN is devoted both to large-scale liquid-sodium experiments with geo- and astrophysical background and to investigations of various energy-related technologies. HZDR is co-founder of the new Center for Advanced Systems Understanding (CASUS), which tackles new challenges in science and computation. Within a large consortium of international partners, HZDR is responsible for the construction of the Helmholtz International Beamline for Extreme Fields (HIBEF) at the European XFEL. It will offer novel experimental opportunities for investigating matter under extreme conditions, plasmas, as well as planetary and strong-field physics. A growing scientific community, from materials sciences to medicine, shows a strongly increasing interest in using the spectral range provided by the far-infrared FELs and the new THz beamline at HZDR. Therefore, a concept is being developed for the Dresden Advanced Light Infrastructure (DALI), a novel facility planned for PoF IV/V that provides unique capabilities for satisfying this demand. Currently, several pilot studies focus on the technical feasibilities. HZDR will provide a CDR in the first year of PoF IV.

6.6. Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research (HZG)

Around 1,000 employees, including 650 scientists, engineers, and technicians, work at HZG in Geesthacht and Teltow (near Berlin). With an annual research budget of about 116 million euros in total, HZG focuses its expertise, infrastructure, and financial resources on a carefully selected number of material systems and processing and characterization methods (approximately 2/3 of the research budget), as well as on the key questions of coastal research. This allows an in-depth treatment of these themes and fosters interdisciplinary and transdisciplinary approaches. HZG conducts research along the value chain, or respectively in value-creating networks, preferably in collaboration with partners from the worlds of science and industry. These research activities connect implementation-inspired basic research with its translation into innovation and application. Research themes at HZG are dedicated to paving the way for a sustainable and life-worthy future by creating scientific solutions for today and tomorrow.

Materials research including characterization is performed in the Research Fields *Information* and *Matter*. Special focus is on the development and optimization of new materials and processes for lightweight construction (e.g. magnesium and titanium alloys and new joining and additive manufacturing technologies), energy and environmental conservation (e.g. effective material separation by membranes and hydrogen technology), and medical technology (e.g. polymer-based and metallic biomaterials). Research projects are driven by interdisciplinary teams of physicists, materials scientists, chemists, biologists, and engineers in order to gain an in-depth understanding of the materials, their properties, and potential applications. Innovative theoretical approaches and digitalization and visualization capabilities are combined with realistic testing and characterization scenarios using cutting-edge analysis methods. The scope of research at HZG on these issues is basically generic, but also extends to specific research in order to implement the generic results into different fields of application. Industrial partners, e.g. systems companies (for the construction of automobiles, ships, aircraft, power stations, chemical process plants, machines, and medical products) and specialized medium-sized high-tech enterprises often join in to realize this task.

Research progress is also promoted by HZG's solution-oriented suite of infrastructures. The Magnesium Innovation Centre (MagIC) focuses on the development of magnesium-based materials for diverse applications (e.g. in the transport and medical sectors), and the Polymer and Hydrogen Technology Centre (PHTC) was established to promote photoelectrochemical hydrogen generation and hydrogen storage as well as the transfer of membrane-based separation technologies into applications. Within the Research Field *Matter*, HZG operates the German

Engineering Materials Science Centre (GEMS), a central user access platform with an exceptional infrastructure for complementary research with photons and neutrons. This close interlocking of materials science and advanced characterization methods provides scientists at HZG with a worldwide unique suite of *in situ* and *operando* observation possibilities. Both for its own research and for the support of external users, HZG fosters and further pursues the consistent development of this outstanding environment for characterizing engineering materials, their processing methods, and their behavior during practical applications.

One central prerequisite for HZG's scientific success in its fields Materials and Coastal Research is its attraction for outstanding national and international scientists. In this context, HZG puts particular emphasis on the promotion of young talents and the management of an optimized work-life balance for all its employees.

6.7. Karlsruhe Institute of Technology (KIT)

KIT – The Research University in the Helmholtz Association – is one of the leading German research institutions with a focus on engineering and the natural sciences as well as a university of excellence within the German excellence strategy since 2019. KIT was founded in 2009 by merging its long-established and well-respected precursor institutions University of Karlsruhe and the Karlsruhe Research Center. Hence, KIT is the only institution in the German science system that has united university and non-university research in one organization. We have thus established a unique research environment that is characterized by scientific excellence, combining the fundamental research of a university with the mission-based research of a national lab.

In addition to approximately 9,500 employees, including over 3,000 doctoral researchers and 2,000 postdoctoral researchers and staff scientists, KIT hosts about 25,000 students. The total annual budget of KIT (≈ 900 million euros per year) is roughly composed of equal shares of state funding, federal funding, and third party funding.

Research, teaching, and innovation are the core tasks of KIT. KIT features a high degree of agility and institutional renewability as well as a dedication to long-term research themes and the preservation of know-how. Accordingly, our research covers the complete range from knowledge-oriented fundamental investigations to applied research, and our projects range from small exploratory undertakings of a few months duration to the long-term large research Programs of the Helmholtz Association. KIT hosts a number of collaborative research centers and two clusters of excellence. Our research infrastructure includes state-of-the-art laboratory equipment, modern information systems, and large-scale experimental facilities. The latter provide important tools and methods for research, open up new research horizons, and are essential drivers of technology developments.

In PoF IV, KIT will contribute significant efforts to 11 Helmholtz Programs in the four Research Fields *Energy*, *Information*, *Matter*, as well as *Earth and Environment*.

In the Research Field *Matter*, KIT is engaged in all three Programs. In the Program MU, KIT plays a leading role in astroparticle physics, particularly with the Pierre Auger Observatory for cosmic rays and the Karlsruhe Tritium Neutrino (KATRIN) experiment. KIT is enhancing its activities in particle and astroparticle theory and is also home of the Tier-1 German data and computing center GridKa. In the Program MT, KIT offers the Karlsruhe Accelerator Technology Platform (ATP) with the Karlsruhe Research Accelerator (KARA) for developing and testing novel concepts for accelerator physics and for synchrotron radiation use. KIT designs, tests, and builds future sensors and detector systems. In the Program MML, KIT employs a comprehensive approach in the use of synchrotron radiation for *in situ* and *operando* characterization of nanostructures, energy materials, devices, and technological processes, as well as high-throughput and even *in vivo* small-animal imaging down to the cellular level.

6.8. Max Planck Institute for Plasma Physics (IPP)

Since IPP was founded in 1960, its research efforts have been strongly directed towards nuclear fusion. Moreover, as a result of close coordination within the European fusion program, a division of responsibility has developed in German magnetic-confinement research: KIT and FZJ cover primarily technological questions, whereas IPP is mainly concerned with the fundamental physics.

Characteristic for IPP is the unique coexistence of strong research efforts in both tokamak and stellarator physics. The institute investigates the physics of high-temperature plasmas in the Wendelstein 7-X stellarator in Greifswald, the largest and conceptionally most advanced stellarator worldwide, as well as in the ASDEX Upgrade tokamak in Garching. These two activities cover a much broader range of properties than would be accessible with each configuration alone. Both the consolidation of existing operating scenarios and the development of new, improved concepts for the operation of ITER, DEMO, and a future fusion power plant form the focus of activities on both devices. In addition, IPP is making contributions to the construction of ITER in its areas of special expertise.

The theory and simulation efforts at IPP are of equal importance. First-principles-based models are replacing (semi-)empirical approaches, e.g. in the crucial area of turbulent transport. With this reorientation, the differences between model developments for tokamak and stellarator configurations have begun to fade. Fluid and kinetic turbulence theory is already conducted largely in the framework of joint projects between the two theoretical divisions in Garching and Greifswald. In close collaboration with these two divisions, the Numerical Methods in Plasma Physics division is developing new numerical methods and algorithms for plasma physics applications. Importantly, theory and simulation allow the building of bridges to basic plasma physics, space plasma physics, and plasma astrophysics.

The understanding of plasma–material interactions and the analysis of new materials, which are to withstand the extreme loading conditions in steady-state devices, are prerequisites for further progress in fusion. In a unique way, IPP combines the investigation of surface and bulk processes under plasma contact at the atomic level, the investigation of tritium-related material physics and chemistry, and the direct link to ASDEX Upgrade, a fusion device that plays a leading role in this area.

In the Research Field *Matter*, IPP is involved in the Program MU:

- Plasma physics for astrophysics and astroparticle physics: The vast majority of the visible universe is a turbulent plasma, and a large part of its energy density is stored in magnetic fields and high-energy charged particles. Thus, plasma effects provide the key to understanding many phenomena in astrophysics, such as black hole accretion disks and cosmic accelerators. IPP will study fundamental processes in astrophysical plasmas, especially turbulence and particle acceleration, in order to promote a deeper understanding of the universe at high energies.
- Electron–positron plasmas in the laboratory: Electron–positron plasmas first formed in the early universe and are still present in the environment of neutron stars and black holes. IPP is aiming to generate and examine a magnetically confined electron–positron plasma for the first time in the laboratory. Such plasmas put the understanding of basic plasma physics to the test, offer the opportunity to develop theoretical models, which are also used in fusion research, and could significantly broaden our understanding of the universe.

7. ORGANIZATION AND GOVERNANCE

7.1. Committees

The Helmholtz-Gemeinschaft Deutscher Forschungszentren (Helmholtz Association of German Research Centers) is a registered association. Its members are 19 research centers, which are legally independent bodies. The central decision-making bodies of the Helmholtz Association are the Assembly of Members and the Senate. The directors of the Helmholtz centers form the Assembly of Members, while the Senate is comprised of representatives of the federal and state governments as well as representatives of science and research, business and industry, and other research organizations.

The Helmholtz Research Fields are essential for the thematic profile of the Helmholtz Association. Following the recommendation of the German Council of Science and Humanities (Wissenschaftsrat) to strengthen the strategic role of the Research Fields, three committees were implemented for each Helmholtz Research Field:

Management Board (MB)

Members of the MB are one scientific director of each of the eight Helmholtz centers involved in the Research Field *Matter* and the three Program spokespersons. The Chief Research Manager *Matter* is invited as guest for specific subjects. The vice president for *Matter* chairs the MB, which meets at least twice a year.

The main tasks of the MB are:

- Developing the strategy of the Research Field,
- Triggering common initiatives, in particular Cross-Cutting Activities,
- Dealing with and prioritizing major investments, and
- Organizing the research within the program-oriented funding.

The MB is assisted by the Coordination Board (CB), which consists of management assistants from the involved centers and Programs. The CB is concerned with the day-to-day work within the Research Field and prepares *inter alia* the meetings of the MB and the Research Field Platform.

In addition to the statutory bodies of the Research Field mentioned above, *Matter* has also established a Steering Committee as an exchange platform to promote discussions on scientific and strategic aspects. The Steering Committee consists of the MB members supplemented by the Topic spokespersons of *Matter*.

Research Field Platform (RFP)

The RFP consists of the MB members and additionally of representatives from the financing partners (federal and states governments). The vice president for *Matter* and one representative of the financing partners together act as co-chairs of the RFP.

The main task of the RFP is the discussion of:

- The strategy of the Research Field developed in the MB,
- The results of the scientific evaluation of the Programs,
- The contributions of the Helmholtz centers to the Programs,
- The recommendations for the content and financing of the Programs for the next funding period, and
- Proposals for strategic investments.

Strategic Advisory Board (SAB)

Members are the chairs of the review panels from the scientific evaluation of the Research Field *Matter*, as well as additional experts to cover the entire range of subjects of the Research Field. The members are elected by the Senate at the suggestion of the president for the duration of one PoF period. Guests are the president of the Helmholtz Association, the vice president for *Matter*, the directors of all participating Helmholtz centers, the Program spokespersons, *Matter*-related members of the Senate, and representatives of the financing partners (federal and states governments).

The main tasks of the SAB comprise:

- Providing scientific and strategic advice for the MB, the RFP, the Senate, and the president,
- Monitoring and controlling the progress and target achievement of the Research Field,
- Discussing the strategic development of the Research Field,
- Giving advice on proposals for strategic investments to prepare decisions of the Senate, and
- Offering independent external scientific consultation for the Research Field *Matter*, the Senate, and the president.

The governance structure of the Research Field *Matter* is shown in Figure 4.

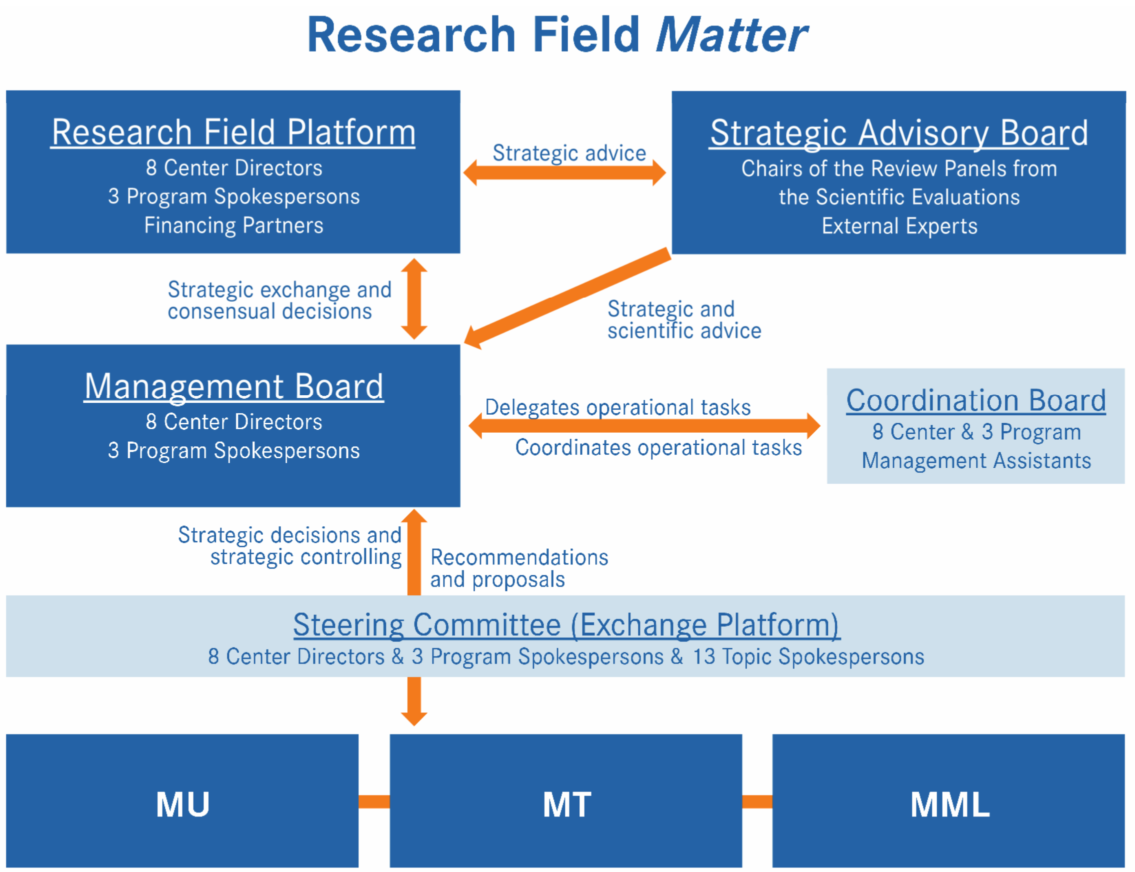

Figure 4: Governance structure of the Research Field *Matter* for PoF IV (2021–2027).

The progress of the scientific work within the Research Field is tracked through annual Program progress reports, which describe the scientific findings and achievements as well as the level of achievement of the milestones. These annual Program reports are the basis for deliberations of the SAB.

8. APPENDIX – LIST OF ABBREVIATIONS

2D/3D	Two-/three-dimensional
3DXRD	3D X-ray diffraction
(HL-)LHC	(High-luminosity) Large Hadron Collider at CERN
(S(C))RF	(Superconducting) radio frequency
(X)FEL	(X-ray) free-electron laser
A	
AD	Antiproton Decelerator, storage ring at CERN
ADC	Analog-to-digital converter
AGIPD	Adaptive Gain Integrating Pixel Detector, detector for the European XFEL
AGISAXS	Anomalous grazing-incidence small-angle X-ray scattering
AIDA	Apparatus for In-situ Defect Analysis, experimental setup at ELBE
AIDA2020	European detector development and testing project
AIM	Advanced Imaging of Matter, cluster of excellence in the German excellence strategy
ALICE	A Large Ion Collider Experiment, experiment at the LHC at CERN
ALP	Axion-like particle
ALPAKA	Abstraction Library for Parallel Kernel Acceleration, open-source code to ease porting applications to new hardware or programming models
ALPS II	Any Light Particle Search II, experiment searching for axions at DESY
AMALEA	Accelerating Machine Learning for Physics, innovation pool project
AMPEL	Alert Management, Photometry and Evaluation of Lightcurves
AMS	Accelerator mass spectrometry
ANKA	Angströmquelle Karlsruhe, synchrotron light source facility at KIT
APEX	A Positron-Electron Experiment
API	Application programming interface
APPA	Atomic and Plasma Physics, and Applied Sciences, research collaboration at FAIR
APPEC	Astroparticle Physics European Consortium
ARPES	Angle-resolved photoemission spectroscopy
ARD/MT-ARD	*Accelerator Research and Development*, Topic in the Program MT
ARIES	Accelerator Research and Innovation for European Science and Society, EU Horizon 2020 project
ARTOF	Angle-resolved time-of-flight spectroscopy
ASAXS	Anomalous small-angle X-ray scattering
ASIC	Application-specific integrated circuit
ATHENA	Accelerator Technology HElmholtz iNfrAstructure, distributed plasma acceleration infrastructure funded by the Helmholtz Association
ATLAS	A Toriodal LHC ApparatuS, experiment at the LHC at CERN
ATP	Accelerator Technology Platform at KIT
Auger	Pierre Auger Observatory, cosmic-ray observatory in Argentina
AXSIS	Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy, ERC synergy grant project

B

BAM	Bundesanstalt für Materialforschung und -prüfung/Federal Institute for Materials Research and Testing
BEER	Beamline for European Materials Engineering Research
BeJEL	Berlin Joint Lab for electron paramagnetic resonance at HZB
BEIChem	Berlin Joint Lab for electrochemical interfaces at HZB
Belle II	Experiment at the SuperKEKB electron–positron collider at KEK
BER II	Berliner Experimentierreaktor II at HZB
bERLinPro	Berlin Energy Recovery Linac Prototype at HZB
BerlQuaM	Berlin Joint Laboratory for Quantum Magnetism at HZB
BerNEM	Berlin Joint Lab for Non Equilibrium of Matter at HZB
BESIII	Beijing Spectrometer III, experiment at the BEPC II collider at IHEP, China
BES-II	Beam Energy Scan program at the RHIC collider at BNL
BESSY II	Berliner Elektronenspeicherring für Synchrotronstrahlung, third-generation soft X-ray light source at HZB
BESSY III	Next generation soft/tender X-ray light source, successor of BESSY II at HZB
BESSY VSR	BESSY – Variable Pulse Length Storage Ring at HZB
BL	Beamline
BMBF	Bundesministerium für Bildung und Forschung/German Federal Ministry of Education and Research
BM@N	Baryonic Matter at Nuclotron, experiment at JINR, Russia
BNL	Brookhaven National Laboratory, USA
Borexino	Real time detector for low energy solar neutrinos at the Laboratori Nazionali del Gran Sasso, Italy
BornAgain	Open source software framework for simulating and fitting neutron and X-ray scattering data, developed under the leadership of FZJ
BrightnESS 2	EU-funded project to support the long-term sustainability of the ESS
BSM	Beyond the Standard Model

C

CALIPSOplus	Coordinated user access program for accelerator-based light sources in Europe and the Middle East
CANS	Compact accelerator-driven neutron source
CARR	Chinese Advanced Research Reactor, close to Beijing
CASPEr	Cosmic Axion Spin Precession Experiment
CASUS	Center for Advanced Systems Understanding, HZDR/UFZ/MPI-CBG/Uniwersytet Wrocławski
CB	Coordination Board (of the Research Field *Matter*)
CBM	Compressed Baryonic Matter, experiment at FAIR
CCA	Cross-Cutting Activity
CCD	Charge-coupled device
CDCS	Center for Data and Computing Sciences, proposed by DESY and the Universität Hamburg
CDR	Conceptual design report
ODS	Oxygen-dispersion strengthened
CEA	French Alternative Energy and Atomic Energy Commission
CEBAF	Continuous Electron Beam Accelerator Facility
CEPC	Circular Electron-Positron Collider, proposed electron–positron collider in China

CERN	Conseil Européen pour la Recherche Nucléaire/European Organization for Nuclear Research in Geneva, Switzerland
CFEL	Center for Free-Electron Laser Science at DESY
CHANDA	Solving Challenges in Nuclear Data For the Safety of European Nuclear Facilities, EU FP7 project
CLIC	Compact LInear Collider, proposed linear electron–positron collider at CERN
CLIO	Centre Laser Infrarouge d'Orsay in France
CML/MU-CML	*Cosmic Matter in the Laboratory*, Topic in the Program MU
CMOS	Complementary metal–oxide–semiconductor
CMS	Compact Muon Solenoid, experiment at the LHC at CERN
CMWS	Centre for Molecular Water Science, proposed at DESY
CORSIKA	Cosmic Ray Simulations for KASCADE, developed at KIT
COSY	Cooler Synchrotron, accelerator at FZJ
CPEDM	Charged particle electric dipole moment
CPU	Central processing unit
CRG	Collaborative research groups at ILL
CRYRING	Heavy ion storage ring at GSI
CSC	Cryogenic stopping cell
CSSB	Centre for Structural Systems Biology at DESY
cSTART	Compact Storage Ring for Accelerator Research and Technology at KIT
CT	Computed tomography
CTA	Cherenkov Telescope Array, next-generation gamma-ray observatory
CUI	The Hamburg Centre for Ultrafast Imaging, former cluster of excellence in the German excellence Initiative, now Advanced Imaging of Matter
CW	Continuous wave
CW SRF	Continuous-wave superconducting radio frequency accelerator
CXNS	Centre for X-ray and Nano Science at DESY
D	
DAF	Detector Assembly Facility, detector R&D and production facility at DESY
DALI	Dresden Advanced Light Infrastructure at HZDR
DAQ	Data acquisition
DARWIN	Dark Matter WIMP Search with Liquid Xenon, proposed experiment at a deep underground laboratory
DASHH	Data Science in Hamburg Helmholtz Graduate School for the Structure of Matter, HIDSS graduate school
DCT	Diffraction contrast tomography
DD4HEP	Open Source Detector Description Toolkit for High Energy Physics Experiments, developed at DESY and CERN
DDL	Distributed Detector Laboratory, infrastructure planned within the Topic MT-DTS
DELTA	Dortmunder Elektronen Testspeicherring-Anlage, storage ring at the Technische Universität Dortmund
DESY	Deutsches Elektronen-Synchrotron in Hamburg and Zeuthen
DESPEC	DEcay SPECtroscopy setup
DFG	Deutsche Forschungsgemeinschaft/German Research Foundation
DIC	Double-implantation chamber
DIDO	Former research reactor at FZJ
DIRC	Detection of internally reflected Cherenkov light, detector that measures the velocity of charged particles
DKFZ	Deutsches Krebsforschungszentrum

DLR	Deusches Zentrum für Luft- und Raumfahrt
DM	Dark matter
DMA/MT-DMA	*Data Management and Analysis*, Topic in the Program MT
DNA	Deoxyribonucleic acid
DORIS	Doppelringspeicher, former second-generation storage ring at DESY
DRACO	Dresden laser acceleration source at HZDR
DREAM	Bispectral powder diffractometer for ESS
DREAMS	Dresden Accelerator Mass Spectrometry, AMS dedicated accelerator for IBC at HZDR
DRESDYN	Dresden Sodium Facility for Dynamo and Thermohydraulic Studies at HZDR
DSB	Double-strand breaks
DSC	Differential scanning calorimetry
DSSC	DEPFET Sensor with Signal Compression, detector for the European XFEL
DTS/MT-DTS	*Detector Technologies and Systems*, Topic in the Program MT
DUNE	Deep Underground Neutrino Experiment, long-baseline neutrino experiment at Fermilab, USA
DWBA	Distorted-wave Born approximation
E	
EBIT	Electron beam ion trap
ECFA	European Committee for Future Accelerators
ECR	Electron cyclotron resonance
ECRAPS	Enabling Technologies for Compact High Rate Photon Sources, innovation pool project
EDDI	Energy dispersive diffraction
EDM	Permanent electric dipole moment
EFNUDAT	European Facility for Nuclear Data Measurements, EU FP6 project
ELAD	Enhanced lateral drift sensors
ELBE	Electron Linac for beams with high Brilliance and low Emittance at HZDR
ELENA	Extra Low Energy Antiproton deceleration ring at CERN
Elettra	Synchrotron light source in Trieste, Italy
EOSC	European Open Science Cloud, EU Horizon 2020 project
EMBL	European Molecular Biology Laboratory
EMFL	European Magnetic Field Laboratory
EMIL	Energy Materials In-Situ Laboratory Berlin at HZB
EMMI	Extreme Matter Institute at GSI
EMSC	Engineering Materials Science Centre at HZG
ERC	European Research Council
ERDA	Elastic recoil detection analysis
ERINDA	European Research Infrastructures for Nuclear Data Applications, EU FP7 project
ERL	Energy-recovery linac
ErUM	Erforschung von Universum und Materie, BMBF framework program for research on the universe and matter
ErUM-Data	Action plan in the framework of ErUM to support the digital transformation in basic research
ErUM-Pro	Action plan in the framework of ErUM to support the networking of universities, research infrastructures, and society in basic research and for technological innovations
ESA	European Space Agency
ESCAPE	European Science Cluster of Astronomy & Particle physics, part of ESFRI
ESFRI	European Strategy Forum on Research Infrastructures
ESR	Experimentier-Speicherring/experiment storage ring at GSI

ESRF	European Synchrotron Radiation Facility in Grenoble, France
ESS	European Spallation Source in Lund, Sweden
ET	Einstein Telescope, proposed European gravitational-wave observatory
eTFF	Electromagnetic transition form factor
eTOF	Endcap time-of-flight detector
EUCALL	European Cluster of Advanced Laser Light Sources, European network of large-scale user facilities for free-electron laser, synchrotron, and optical laser radiation and their users
EUCARD	European Coordination for Accelerator Research & Development, EU FP7 project
EuPRAXIA	European Plasma Research Accelerator with eXcellence in Applications, EU Horizon 2020 project
EUV	Extreme ultraviolet
European XFEL	European X-ray Free-Electron Laser in Hamburg and Schenefeld
EU-SMI	European Soft Matter Infrastructure, EU Horizon 2020 project
EXAFS	Extended absorption fine structure
EXL	Exotic nuclei studied with Electromagnetic and Light hadronic probes, experiment at FAIR

F

FAIR	Facility for Antiproton and Ion Research at GSI
FAIR principle	Findable, accessible, interoperable, and re-useable data
FCC	Future Circular Collider, proposed electron–positron and hadron–hadron collider at CERN
FEL	Free-electron laser
FELBE	Free-electron laser at ELBE
FELs of Europe	Collaboration of all free-electron laser facilities in Europe
FELIX	Free Electron Laser for Infrared Experiments at Radboud Universiteit Nijmegen, the Netherlands
FEM	Finite-element method in computer simulation
Fermilab	Fermi National Accelerator Laboratory near Chicago, USA
FERMI@Elettra	Free-electron laser Radiation for Multidisciplinary Investigations at Elettra
FHI	Fritz Haber Institute of the Max Planck Society
FIB-SXM	Focused ion beam milling scanning X-ray microscopy
FLAIR	Facility for Low-Energy Antiproton and Ion Research at GSI
FLARE	Free-electron Laser for Advanced spectroscopy and high-Resolution Experiments at the FELIX Laboratory
FLASH	Free-Electron Laser in Hamburg at DESY
FLASH2020+	Upgrade project for FLASH
FLASHForward	Plasma wakefield acceleration experiment at FLASH at DESY
FLIM	Fluorescence lifetime imagine
FLUTE	Ferninfrarot Linac und Test Experiment at KIT
FOM	Foundation for Fundamental Research on Matter, part of the Netherlands Organization for Scientific Research
FPF/MU-FPF	*Fundamental Particles and Forces*, Topic in the Program MU
FPGA	Field programmable gate arrays
FRAP	Fluorescence recovery after photobleaching
FRET	Fluorescence resonance energy transfer
FRG-1	Forschungsreaktor Geesthacht 1/research reactor at HZG
FRJ-2	Forschungsreaktor Jülich 2/research reactor at FZJ
FRM II	Forschungsneutronenquelle Heinz Maier-Leibnitz/research neutron source at the Technische Universität München
FT	Facility Topic

FTE	Full-time equivalent (personnel)
FZJ	Forschungszentrum Jülich GmbH
G	
GANIL	Grand Accélérateur National d'Ions Lourds in Caen, France
GCOS	Global Cosmic Ray Observatory
GELINA	Geel Electron LINear Accelerator Facility, neutron source in Geel, Belgium
GEM	Gas electron multiplier
GEMS	German Engineering Materials Science Centre at HZG
GI	Grazing incidence
GiPS	Gamma-induced positron spectroscopy
GISANS	Grazing-incidence small-angle neutron scattering
GISAXS	Grazing-incidence small-angle X-ray scattering
GLAD	GSI Large-Acceptance Dipole magnet
GmbH	Gesellschaft mit beschränkter Haftung, type of legal entity in Germany
GMR	Giant magnetoresistance
GPU	Graphics processing unit
GRAND	Giant Radio Array for Neutrino Detection, proposed neutrino experiment
GridKa	Karlsruhe Grid Computing Centre, Tier-1 center at KIT
GSI	Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt
GUT	Grand unified theory
H	
HADES	High Acceptance Di-Electron Spectrometer, experiment at GSI
HAICU	Helmholtz Incubator platform for Artificial Intelligence
HARWI	Hard Wiggler Beamline at HZG
HASYLAB	Hamburger Synchrotronstrahlungslabor at DESY
HBS	High Brilliance Neutron Source at FZJ
HCI	Highly charged ions
HDRI	High Data Rate Processing and Analysis Initiative
HED	High energy density
HEIBRIDS	Helmholtz Einstein International Berlin Research School in Data Science, HIDSS graduate school
HEMCP	Helmholtz Energy Materials Characterization Platform at HZB
HEMS	High-Energy Materials Science Beamline at HZG
HEP	High-energy physics
HERA	Former Hadron–Electron Ring Accelerator at DESY
HESR	High Energy Storage Ring
H.E.S.S.	High Energy Stereoscopic System, gamma-ray observatory in Namibia
HE-II	High-Energy Ion Implantation facility at HZDR
HE-LHC	High-Energy Large Hadron Collider at CERN
HFM	High Field Magnet at HZB
HFML	High Field Magnet Laboratory, Radboud Universiteit Nijmegen, the Netherlands
HGF	Helmholtz-Gemeinschaft Deutscher Forschungszentren/Helmholtz Association of German Research Centres
HGHG	High-gain harmonic generation
HGS-HIRe for	Helmholtz Graduate School for Hadron and

FAIR	Ion Research
HI	Helmholtz Institute
HIB	Helmholtz International Beamline, user consortium at the European XFEL
HIBEF	Helmholtz International Beamline for Extreme Fields at the European XFEL
HIDSS	Helmholtz Information & Data Science Schools
HIFIS	Helmholtz Information and Data Science platform
HI Jena/HIJ	Helmholtz Institute Jena
HIM	Helmholtz Institute Mainz
HIM	Helium ion microscope
HIP	Helmholtz Incubator platform for Imaging
HIRSAP	Helmholtz International School for Astroparticle Physics and Enabling Technology
HISPEC	High-Resolution In-Flight Spectroscopy setup at FAIR
HIT	Heidelberger Ionenstrahl-Therapiezentrum at the Universitätsklinikum Heidelberg
HITRAP	Heavy Ion Trap at GSI
HHG	High-harmonic generation
HLD	Dresden High Magnetic Field Laboratory at HZDR
HL-LHC	High-Luminosity Large Hadron Collider at CERN
HMGU	Helmholtz Zentrum München – Deutsches Forschungszentrum für Gesundheit und Umwelt
HMI	Hahn-Meitner-Institut (now HZB)
HoBiCat	Horizontal b-cavity testing facility at HZB
HOM	High-order mode
HPC	High-performance computing
hRIXS	Heisenberg Resonant Inelastic X-ray Scattering, user consortium at the European XFEL
HTC	Hydrogen Technology Centre at HZG
HVCMOS	High-voltage CMOS
HVF	Helmholtz Validation Fund/Helmholtz-Validierungs-Fonds
HZB	Helmholtz-Zentrum Berlin für Materialien und Energie
HZDR	Helmholtz-Zentrum Dresden-Rossendorf
HZI	Helmholtz-Zentrum für Infektionsforschung/Helmholtz Centre for Infection Research in Braunschweig
HZG	Helmholtz-Zentrum Geesthacht – Zentrum für Material- und Küstenforschung/Centre for Materials and Coastal Research
I	
IA-SFS	Integrating Activity on Synchrotron and Free-Electron Laser Science, EU FP6 project
IAXO	International Axion Observatory, proposed axion search experiment
IBA	Ion beam analysis
IBAD	Ion-beam-assisted deposition
IBC	Ion Beam Center at HZDR
IBL	Imaging Beamline at HZG
IceCube	Neutrino observatory at the South Pole
IceCube-Gen2	Proposed upgrade of IceCube
ICFA	International Committee for Future Accelerators
IDAF	Interdisciplinary Data and Analysis Facility, LK II Infrastructure associated with MT
IDS	Information and data science
IFF	Institut für Festkörperforschung at FZJ
IFW	Leibniz-Institut für Festkörper- und Werkstoffforschung/Leibniz Institute for Solid State and Materials Research in Dresden

IKP	Institut für Kernphysik/Nuclear Physics Institute at FZJ
IL	Ionoluminescence
ILC	International Linear Collider, proposed linear electron–positron collider
ILIMA	Isomeric beams, LIfetimes and Masses measured in storage rings, experiment at FAIR
ILL	Institut Laue-Langevin in Grenoble, France
IµP	Ion microprobe
InnoMatSy	Innovationsplattform für lasttragende und multifunktionale Materialsysteme
IP	Intellectual property
IPP	Max Planck Institute for Plasma Physics in Garching and Greifswald
IPSUS	Improving Performance and Productivity of Integral Structures through Fundamental Understanding of Metallurgical Reactions in Metallic Joints, Helmholtz Virtual Institute
IR	Infrared
ISIS	Pulsed neutron and muon source at Rutherford Appleton Laboratory in Didcot, UK
ISL	Former Ionenstrahllabor/ion beam laboratory at HZB
ISOLDE	Isotope Mass Separator On-Line facility at CERN
ISS	Former Institut für Synchrotronstrahlung/Institute for Synchrotron Radiation at KIT
IVF/INF	Helmholtz Impuls- und Vernetzungsfonds/Helmholtz Initiative and Networking Fund
J	
JARA	Jülich-Aachen Research Alliance
JARA-SOFT	Jülich Aachen Research Alliance-Researching Soft Matter
JARA-FIT	Jülich Aachen Research Alliance-Fundamentals of Future Information Technology
JCNS	Jülich Centre for Neutron Science at FZJ
JLAB	Thomas Jefferson National Accelerator Facility in Newport News, USA
JLSR	Joint Laboratory of Structure Research at HZB
JPR	Josephson plasmon resonance
JSNS	Japanese Spallation Neutron Source at the Japan Proton Accelerator Research Complex
JUNO	Jiangmen Underground Neutrino Observatory at Kaiping, China
JuSPARC	Peta-Watt laser center for ultra-fast studies and polarized beams at FZJ
K	
KALDERA	Project to develop high-power lasers and their use at DESY
KALYPSO	KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy, developed at KIT
KAPTURE	Karlsruhe Pulse Taking Ultra-Fast Readout Electronics, developed at KIT
KARA	Karlsruhe Research Accelerator at KIT
KASCADE	Karlsruhe Shower Core and Array Detector-Grande, former air shower experiment array
KAT	Komitee für Astroteilchenphysik/German Committee for Astroparticle Physics
KATRIN	Karlsruhe Tritium Neutrino Experiment at KIT
KEK	High Energy Accelerator Research Organization, Japanese national laboratory for particle physics in Tsukuba
KET	Komitee für Elementarteilchenphysik/German Committee for Elementary Particle Physics
KFN	Komitee Forschung mit Neutronen/German Committee for Research with Neutrons
KHuK	Komitee für Hadron- und Kernphysik/German Committee for Hadron and Nuclear Physics
KIT	Karlsruhe Institute of Technology
KNMF	Karlsruhe Nano Micro Facility at KIT
KSETA	Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology

L	
Lambda	Hybrid-based detector at the European XFEL
LASPEC	Laser Spectroscopy of short-lived nuclei, experiment at FAIR
LBNF	Long Baseline Neutrino Facility at Fermilab, USA
LBNL	Lawrence Berkeley National Laboratory, USA
LCLS	Linac Coherent Light Source, X-ray FEL at SLAC, USA
LCLS-II	Upgrade project of the LCLS at SLAC, USA
LEAPS	League of European Accelerator-based Photon Sources
LENS	League of advanced European Neutron Sources
LEU	Low-enriched uranium
LFU	Lepton flavor universality
LGAD	Low-gain avalanche diode
LHC	Large Hadron Collider at CERN
LHCb	Large Hadron Collider Beauty experiment at the LHC at CERN
LIGA	Lithographie, Galvanik und Abformung/Lithography, electroplating and moulding
LINAC	Linear accelerator
LK I	Leistungskategorie I, Helmholtz nomenclature to describe funding for research
LK II	Leistungskategorie II, Helmholtz nomenclature to describe funding for infrastructures
LLNL	Lawrence Livermore National Laboratory in Livermore, USA
LLRF	Low-level radio frequency
LNCMI	Laboratoire National des Champs Magnétique Intenses in Grenoble and Toulouse, France
LNV	Lepton number violation
LSDMA	Large Scale Data Management, cross-program activity in PoF III
LSF	Large-scale facilities
LUXE	Laser Und XFEL Experiment, test of quantum physics at the European XFEL using high-intensity laser at DESY
LWFA	Laser wakefield acceleration
M	
µCT	Micro-computed tomography
MagIC	Magnesium Innovation Centre at HZG
MAGIC	Magnetism Single Crystal Diffractometer for the ESS
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescope on La Palma, Spain
MAM	Matter–antimatter asymmetry section of the Helmholtz Institute Mainz
MAMI	Mainz Microtron at the Johannes Gutenberg-Universität Mainz
MATS	Measurements with an Advanced Trapping System, part of the experimental program NUSTAR at FAIR
MatSEC	Graduate School Materials Science for Solar Energy Conversion at the Dahlem Research School in Berlin
MB	Management Board (of the Research Field *Matter*)
MBA	Multibend achromat
MBE	Molecular beam epitaxy
MBI	Max-Born-Institut in Berlin
MD	Molecular dynamics
MDC	Max Delbrück Center for Molecular Medicine in Berlin
MePS	Monoenergetic positron source

Mfps	Mega frames per second
MHD	Magnetohydrodynamics
microTCA	Micro Telecommunications Computing Architecture
ML	Machine learning
MLS	Metrology Light Source at PTB
MLZ	Heinz Maier-Leibnitz Zentrum in Garching
MMC	Metallic magnetic calorimeters
MML	*From Matter to Materials and Life*, Helmholtz Program in the Research Field *Matter*
MML-Matter	*Matter – Dynamics, Mechanisms and Control*, Topic in the Program MML
MML-Materials	*Materials – Quantum, Complex and Functional Materials*, Topic in the Program MML
MML-Life	*Life Sciences – Building Blocks of Life: Structure and Function*, Topic in the Program MML
MOCVD	Metal-organic chemical vapour deposition
MoU	Memorandum of Understanding
MOVPE	Metal-organic vapor phase epitaxy
MPG	Max-Planck-Gesellschaft/Max Planck Society
MPI	Max-Planck-Institut/Max Planck Institute
MRI	Magneto-rotational instability
MR-TOF-MS	Multiple-reflection time-of-flight mass spectrometer/separator
MRU/MU-MRU	*Matter and Radiation from the Universe*, Topic in the Program MU
MS	Magnetron sputtering
MSV	Modularized start version
MT	*Matter and Technologies*, Helmholtz Program in the Research Field *Matter*
MT-ARD/ARD	*Accelerator Research and Development*, Topic in the Program MT
MT-DMA/DMA	*Data Management and Analysis*, Topic in the Program MT
MT-DTS/DTS	*Detector Technologies and Systems*, Topic in the Program MT
MU	*Matter and the Universe*, Helmholtz Program in the Research Field *Matter*
MU-CML/CML	*Cosmic Matter in the Laboratory*, Topic in the Program MU
MU-FPF/FPF	*Fundamental Particles and Forces*, Topic in the Program MU
MU-MRU/MRU	*Matter and Radiation from the Universe*, Topic in the Program MU

N

NAF	National Analysis Facility, scientific computing facilities at DESY and at GSI
NEAT	Cold neutron time-of-flight spectrometer at HZB
NEDENSAA	Neutron Detector Developments for Nuclear Structure, Astrophysics and Applications
NESR	New Experimental Storage Ring at GSI
NFDI	Nationale Forschungsdateninfrastruktur/National research data infrastructure
NFFA	Nanoscience Foundries and Fine Analysis, EU FP7 project
NHMFL	National High Magnetic Field Laboratory in Tallahassee, USA
NIST	National Institute of Standards and Technology in Gaithersburg, USA
NMI3	European Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy, EU FP7 project
NMR	Nuclear magnetic resonance
NOVA ERA	Neutrons Obtained Via Accelerator for Education and Research Activities, proposed CANS source for universities by JCNS
NRA	Nuclear reaction analysis
NSE	Neutron spin echo spectroscopy
NuPECC	Nuclear Physics European Collaboration Committee

NUSTAR	Nuclear Structure, Astrophysics and Reactions, experimental program at FAIR
O	
ODS	Oxide dispersion strengthened
OnDA	Online data analysis and feedback for serial X-ray imaging
ORNL	Oak Ridge National Laboratory, USA
P	
PANDA	AntiProton Annihilation at Darmstadt, experiment at FAIR
PAX	Positron-Accumulation-Experiment
PBII	Plasma-based ion implantation
PENELOPE	Petawatt, Energy-Efficient Laser for Optical Plasma Experiments at HZDR
PET	Positron emission tomography
PETRA III	Positron-Elektron-Tandem-Ring-Anlage, third-generation synchrotron radiation source at DESY
PETRA IV	Project to upgrade the PETRA III synchrotron radiation source at DESY to a diffraction-limited source
PG-C	Peter Grünberg Centre at FZJ
PHELIX	Petawatt High Energy Laser for Heavy Ion Experiments at GSI
PHGS	PIER Helmholtz Graduate School
PHTC	Polymer and Hydrogen Technology Centre at HZG
PI	Principal investigator
PIER	Partnership for Innovation, Education and Research between DESY and the Universität Hamburg
PIConGPU	Many-GPGPU particle-in-cell code, developed at HZDR
PIGE	Particle-induced gamma-ray emission
PIK	High-flux research reactor at the Petersburg Nuclear Physics Institute, Russia
PITZ	Photoinjector test facility at DESY in Zeuthen
PIXE	Particle-induced X-ray emission
PoF	Programmorientierte Förderung/Program-oriented funding
POLI	Polarized hot neutron diffractometer
POWTEX	High-intensity time-of-flight diffractometer
PRISMA	Precision Physics, Fundamental Interactions and Structure of Matter, cluster of excellence in the German excellence initiative
PSI	Paul Scherrer Institute in Villigen, Switzerland
PTB	Physikalisch-Technische Bundesanstalt/German national metrology institute in Braunschweig and Berlin
PTC	Polymer Technology Centre at HZG
PWFA	Beam-driven plasma wakefield acceleration
Q	
QCD	Quantum chromodynamics
QED	Quantum electrodynamic
QGP	Quark–gluon plasma
QOS	Quality of service
QURS	Quantum Universe Research School

R

R3B	Reactions with Relativistic Radioactive Beams, experiment at FAIR
R&D	Research and development
RBE	Relative biological effectiveness
RBS	Rutherford backscattering spectrometry
RDMA	Remote direct memory access
REGAE	Relativistic Electron Gun for Atomic Exploration, electron accelerator experiment within the framework of CFEL
RF	Radio frequency
RFP	Research Field Platform (*of the Research Field Matter*)
RIKEN	Rikagaku Kenkyūsho, Japanese National Institute of Physical and Chemical Research
RIXS	Resonant inelastic X-ray scattering
RNA	Ribonucleic acid
Root	Open-source project for data analysis and visualization
RTG	Research Training Group/Graduiertenkolleg, DFG funding scheme

S

S4M	Shared, scalable solutions for science in Matter Portal, web-based portal to organize the exchange between MT-DMA and other Topics and Programs of the Research Field *Matter*
SAB	Strategic Advisory Board (of the Research Field *Matter*)
SANS	Small-angle neutron scattering
SAS	Small-angle scattering
SASE	Self-amplified spontaneous (or stimulated) emission
SAXS	Small-angle X-ray scattering
SC	Superconducting/superconductor
SACLA	SACLA Science Research Group at RIKEN, Japan
SCCS	SPring-8, synchrotron radiation source at RIKEN, Japan
SCRF	Superconducting Radio Frequency
SEM	Scanning electron microscopy
SFB	Sonderforschungsbereich/Collaborative research center, DFG funding scheme
SFX	Serial Femtosecond Crystallography beamline at the European XFEL
SHE	Superheavy elements
SHIP	Separator for Heavy Ion reaction Products at GSI
SHIPTRAP	Ion trap facility for superheavy elements at GSI
SIMS	Secondary-ion mass spectrometry
SINBAD	Short INnovative Bunches and Accelerators at DESY, accelerator research and development facility
SINE 2020	Science and Innovation with Neutrons in Europe, EU Horizon 2020 program
SINQ	Spallationsinduzierte Neutronenquelle/Swiss Spallation Neutron Source at PSI
SiPM	Silicon photomultiplier
SIS100	Schwerionen-Synchrotron/heavy-ion synchrotron at GSI
SIS18	Schwerionen-Synchrotron/heavy-ion synchrotron at GSI
SKADI	SANS instrument for the ESS
SLAC	Stanford Linear Accelerator Center in Menlo Park, USA
SLM	Selective laser melting
SLS	Swiss Light Source at PSI

SM	Standard Model of particle physics
SN	Supernova
SNIM	Scanning near-field infrared microscopy
SNS	Spallation Neutron Source at Oak Ridge National Laboratory, USA
SPARC	Stored Particle Atomic Physics Research Collaboration at GSI
SPES	Short-Pulse Engineering Spectrometer at HZG
SPONSOR	Slow POsitroN System Of Rossendorf at HZDR
SQUID	Superconducting quantum interference device
SR	Synchrotron radiation
SRS	Synchrotron Radiation Source at Daresbury Laboratory in Cheshire, UK
ST	Subtopic
STS	Silicon Tracking System of the CBM experiment at FAIR
Super-FRS	Superconducting Fragment Separator at FAIR
SupraLab	Application laboratory for developing CW SC accelerator technology at HZB
SX-FragS	Serial crystallography for fragment screening, innovation pool project
s-SNIM	THz/mid-IR nanoscopy
T	
TAS	Triple-axis spectrometer
TASCA	TransActinide Separator and Chemistry Apparatus at GSI
TBONE	THz Beam Optics for New Experiments at KIT
TDC	Time-to-digital converter
TDR	Technical design report
TEM	Transmission electron microscopy
TESLA	Tera-Electronvolt Superconducting Linear Accelerator, former proposed superconducting linear electron–positron collider
Tier	Element of the computing model of the WLCG
Tier-2	Second-level element of the WLCG, which brings the WLCG services to a country or region
TISANE	Time-involved small-angle neutron experiments
TLK	Tritium Laboratory Karlsruhe
TNSA	Target normal sheath acceleration
TOF	Time of flight
TPC	Time projection chamber
TR	Time-resolved
TransFAIR	Activities of the FZJ Institut für Kernphysik planned to be transferred to GSI during PoF IV
TRB	Trigger and read-out board
TRISTAN	Tritium Investigation on Sterile Neutrinos with KATRIN at KIT
TRIUMF	Canada's national particle accelerator center in Vancouver, Canada
TTF	TESLA Test Facility at DESY
T-REX	Bispectral Chopper Spectrometer for the ESS
TWAC	Terawatt Accumulator Project at the Institute for Theoretical and Experimental Physics in Moscow, Russia
U	
UFO	Suite of open-access DAQ software developed and used in beam-monitoring systems
ULSI	Ultralarge-scale integration
ULTRASAT	Ultraviolet Transient Astronomy Satellite

UNILAC	Universal Linear Accelerator at GSI
UV	Ultraviolet
V	
VERITAS	Very Energetic Radiation Imaging Telescope Array System at the Fred Lawrence Whipple Observatory, USA
VUV	Vacuum ultraviolet
W	
WASA	Wide Angle Shower Apparatus at COSY
WAXS	Wide-angle X-ray scattering
WANS	Wide-angle neutron scattering
WDM	Wavelength division multiplexing
WDM	Warm dense matter
WIMP	Weakly interacting massive particle
WLCG	Worldwide LHC Computing Grid
WPC	Wolfgang Pauli Centre for Theoretical Physics, proposed at DESY
X	
XUV	Extreme ultraviolet
XFEL	X-ray free-electron laser
XRootD	Open-source project to provide high-performance, scalable, fault-tolerant access to data repositories of many kinds
X-PCS	X-ray photon correlation spectroscopy
Y	
YIG	Helmholtz Young Investigator Group
Z	
ZEA	Zentralinstitut für Engineering, Elektronik und Analytik/Central Institute of Engineering, Electronics and Analytics at FZJ