Strategy paper of the research field Matter in the Helmholtz Association

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Program-oriented funding 2021 – 2027

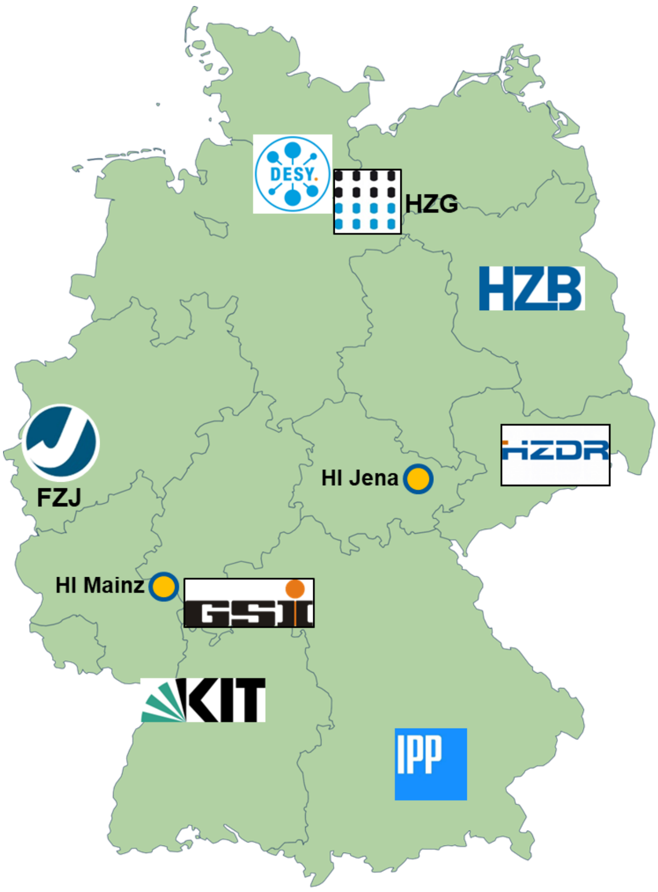
1 OVERVIEW OF THE RESEARCH FIELD MATTER

In the research field Matter, the Helmholtz Association bundles its expertise in fundamental 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 and detector concepts.

1.1 Current research portfolio and participating centers

The scientific mission of the research field is the exploration of 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 on different length scales also serves as a basis for the development of new materials and drugs. This mission is pursued by eight centers (see figure 1) which make focused and dedicated use of large-scale research facilities, which they continuously develop further. 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.

A short description of the centers within the research field Matter is presented below:



	LK II (User facilities)	International Research Infrastructures	National Research Infrastructures
DESY	FLASH PETRA III IDAF	LHC BELLE II CTA (under construction) Icecube XFEL	CFEL CSSB NanoLab DESY Testbeams DAF HIB@XFEL PITZ
FZJ	JCNS (in MLZ)	ESS (under construction) ILL	(FRM-II)
GSI	UNILAC SIS18 ESR	FAIR (under construction) ALICE	HI Jena HI Mainz EMMI HICforFAIR
HZB	BESSY II / BESSY VSR		bERLinPro SupraLab EMIL
HZDR	ELBE HLD IBC	XFEL EMFL ESRF	HIB@XFEL DRESDYN
HZG	GEMS-p GEMS-n	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 program-oriented funding period IV (2021-2027).

DESY is one of the world's leading accelerator centers. For a wide range of applications across disciplines and for national and international groups of researchers, DESY operates the synchrotron radiation source PETRA III exploiting tender to hard X-rays, the soft X-ray free-electron laser

FLASH mainly for research at ultra-short time scales, the superconducting accelerator of the X-ray laser European XFEL. DESY is among others cooperation partner of the LHC in Geneva, of IceCube and CTA and is the German shareholder of the ESRF in Grenoble and the XFEL in Hamburg. DESY’s research activities are organized in four fields: particle and astroparticle physics, research with synchrotron and FEL radiation and accelerator R&D. Every year, more than 3,000 scientists mainly from Germany and Europe but also from other parts of the world use the large-scale research facilities at DESY.

FZJ Forschungszentrum Jülich GmbH is one of the largest research institutions in Europe. Within interdisciplinary research, a particular strength is the development, provision and application of outstanding research infrastructures and expertise across all methods. FZJ bundles all its competences in neutron research in the Jülich Center for Neutron Science which has outposts at MLZ in Garching and at international most powerful neutron sources. Moreover, it plays a leading role in the German involvement in the European Spallation Source ESS and the development of a compact neutron source. For PoF IV a transfer of all activities related to the Jülich expertise in the field of accelerator and hadron physics to GSI is planned.

GSI with its two institutes at the universities of Jena and Mainz belongs to the world-wide leading accelerator centers for hadron and nuclear physics, and for atomic physics with storage rings. Contributing with all its activities to Matter, GSI conducts in addition research into dense plasma physics and application-relevant fields, such as materials research, radiobiological studies, cancer therapy with ion beams and space radiation research in close collaboration with ESA. Moreover, GSI strongly contributes to the ALICE experiment at CERN-LHC. The major thrust of GSI is the construction and commissioning of the international Facility for Antiproton and Ion Research FAIR in Darmstadt, with the participation of more than 3,000 scientists from more than 50 countries.

HZB focuses on energy and materials research and it operates the light source BESSY II for the national and international user community coming from diverse scientific disciplines. The recently inaugurated “Energy Materials In-Situ Laboratory” at BESSY pioneers a novel approach in energy materials research. BESSY II produces VUV/soft X-ray radiation which is used every year by more than 3000 users from all over the world. Accelerator research at HZB is the basis for the operation of BESSY II and the Metrology Light Source (MLS), as well as for the development of BESSY II into a variable pulse-length storage ring (BESSY VSR). HZB is currently identifying the user-driven requirements for a diffraction limited future light source in the soft X-ray range (“BESSY III”). Highest stability enabling nanometer spatially resolved experiments with unprecedented spectral resolution will be a key aspect of this facility.

HZDR within research field Matter conducts research on magnetism and strongly correlated materials, materials for energy and information, on magnetohydrodynamics as well as on physics and materials science with ion beams and under highest electromagnetic fields utilizing its large-scale facilities and it develops future technologies for high-power lasers and accelerators. HZDR operates the research infrastructures Ion Beam Center (IBC), Dresden High Magnetic Field Laboratory (HLD) and the ELBE Center for High Power Radiation Sources. Moreover, it currently constructs the DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN). The research center plays a leading role in the construction and operation of the Helmholtz International Beamlines (HIB) at the European XFEL.

HZG research encompasses materials science and coastal science. Materials research focuses on structural and functional material systems, biomaterials for application in medicine and materials development and characterization with synchrotron radiation and neutrons. For these purposes HZG participates in the HGF-research fields Key Technologies (Information) and Matter, in the latter with GEMS (GEMS-p, GEMS-n) offering unique research infrastructures for materials sciences at PETRA III and FRM II.

IPP at Garching and Greifswald carries out experimental and theoretical research in high temperature plasma physics as well as in directly related materials science. IPP operates and exploits two large experiments, ASDEX Upgrade and Wendelstein 7-X, as well as several smaller experiments, supported by a strong theory and simulation effort. In addition, IPP entertains a range of activities in plasma astrophysics, investigating the origin and role of turbulence, magnetic fields, and energetic particles (cosmic rays) in the Universe. IPP participates in the research fields Energy and in future in the research fields Matter and Information.

KIT – The Research University in the Helmholtz Association – is one of the leading German research institutions with a focus on engineering and natural sciences. In the research field Matter, KIT makes significant contributions to all three research programs, having a leading role in astroparticle physics, particularly with the Auger observatory for cosmic rays and the Karlsruhe Tritium Neutrino experiment KATRIN. KIT is enhancing its activities in particle and astroparticle theory and it is also home of the Tier-1 German data and computing center GridKa. Within the Karlsruhe Accelerator Technology Platform (ATP), KIT develops and tests novel concepts for accelerator physics and the use of synchrotron radiation. KIT designs, tests and builds future sensors and detector systems.

1.2 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, this research field operates state-of-the-art research infrastructures which have an impact on research that exists nowhere else.

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

The user operation of our research facilities (performance category LK II[1]) 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 a 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 a European initiative (LEAPS – League of European Accelerator-Based Photon Sources) for a stronger cooperation between the national research facilities and for a better integration (common standards, technology roadmaps, agreement in the scientific portfolio). The League of advanced European Neutron Sources (LENS) is founded to similarly integrate the neutron community, in which the research field will seek an active role.

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

1.3 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 the implementation of our own research targets and they provide access to national and international teams of researchers after going through a Peer Review Procedure. Every year, more than 10,000 scientists use our modern experimental stations. Indeed, the time available for experiments is mostly multiple oversubscribed, with increasing tendency. Thus, research at Helmholtz large-scale facilities is the paradigm of a highly efficient cooperation strategy between universities and non-university research institutes.

With a complementary organized portfolio of large-scale research facilities, the Helmholtz Association plays the role of an architect worldwide. The large-scale facilities of the research field are interdisciplinary research platforms, which play an indispensable part in projects of physicists, chem-

[1] LK II: User facilities

ists and 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 our 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 shall move into focus more and more.

The research field centers are strategic partners of renowned international large-scale research facilities of 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 is a unique feature of the Helmholtz Association and it substantially contributes 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 CHALLENGES OF THE COMING 5 – 10 YEARS

Key scientific challenges which will be addressed by the research field Matter in the next funding period include first answers to the following questions (see 2.1.):

- 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 discovery 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 which will emerge from the advanced facilities in particle and astroparticle physics as well Synchrotron radiation and FEL facilities as a major challenge in the upcoming funding period which requires particular attention. This will be addressed in more detail in (2.2. and 2.4.).

A further challenge of Matter concerns the development of its large scale facilities and the participation in international large-scale projects which require upgrade strategies of national facilities to maintain a world-leading position, the successful participation in the construction, commissioning and in the data harvest at European and international facilities. This will further discussed in (2.3.) and (3.4.).

The transfer of knowledge and emerging technologies to society and to the market is an increasing strategic activity in Matter as discussed in some detail in (3.6.).

Finally, the global competition to attract the best brains is a continuous challenge, also in the upcoming funding period (see 3.7.).

2.1 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 opened up completely new perspectives for testing the Standard Model and for the search for physics beyond the Standard Model. The LHC is the only facility worldwide for such studies at highest energies and smallest length scales. Complementary tests of the Standard Model are made possible with extreme precision measurements at heavy quarks. Neutrinos confront us also with unsolved mysteries. Its properties and various roles from the Big Bang up to explosions of stars are still not being understood. What is neutrino mass? Are there more than the identified three kinds of neutrinos? The universe consists of only 5 percent of normal matter, the rest we understand only rudimentarily. What is dark matter which so far is 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 strong interaction. But how does complexity, which 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 nuclear constituents, and how can their interaction be derived from QCD? How does the phase diagram of nuclear matter look like? Which role do hadrons, nuclei and nuclear matter play for the evolution of the universe and the creation of elements? How does 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. The energy reaches up to a hundred million times the energy which is 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 which 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 which are multi-functional and blur the delimitations between metals, isolators, semiconductors and organic-biological systems. This requires novel interdisciplinary strategies for synthesis and for the non-destructive *operando* analysis.

- **We decode complex biological structures and processes**
  Structural biology faces a change of paradigms. This is caused by the enormous successes in the development of cryo-electron microscopy and the new possibilities provided by the free-electron laser European XFEL. 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 native surroundings and in real-time. The application of all these techniques will allow bridging 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 and future user facilities as European XFEL and FAIR at the top of global research. For future experiments, we will generate and characterize particle beams of highest density, highest performance, highest brilliance and ultra-short pulse length in the attosecond range. The further development of the superconducting accelerator technology continues to be a central challenge.

- **We analyze the physical mechanisms of plasma acceleration**
  The acceleration of charged particles opens the way to novel ultra-compact accelerators. Much progress in the understanding of accelerator mechanisms and 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 which will make possible the ultimate energy and spatial resolution near the quantum noise. We will individually tailor the properties in particular of semiconductor sensors according to the particular 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 Matter.

2.2 Technological challenges

To achieve our goals we must create the necessary technological preconditions. This generally involves pushing the limits of the 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 at the LHC confronts the detectors with enormous challenges. Construction and commissioning of the detectors is a central goal of the coming years. Here, DESY will assume a central role in Germany and worldwide.
- **Development of novel sensors and detector systems for future experiments in matter**
  With the rapidly increasing performance of accelerators and radiation sources and with large new observatories, detector systems and the gain of knowledge from data must keep pace. The number of pixels and the integration density of particles and X-ray detectors massively increase and this allows 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 develop the superconducting radio frequency technology for the efficient CW operation and new concepts and technologies to fulfill the increasing demands concerning beam intensity, stability and quality. We 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 for the use of plasma acceleration is to demonstrate its application in an accelerator under realistic conditions. For this purpose, we develop a concept for this kind of accelerator and 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 Matter and respond to the diverse needs of the science they do by systematically developing our already excellent capabilities.

2.3 Further development of large-scale facilities

The mission of the research field Matter is critically coupled to the use of large-scale research facilities which operate at the limit of current technologies (see chapter 3.4). 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, the participation in the construction of international facilities and in the preparation of technical design reports and visibility studies of potential future facilities.

Upgrades of national facilities

- **BESSY VSR and BESSY III**
  Within the funding period (2021-2027), the new BESSY VSR technology will be installed in the existing storage ring and will commence user operation. BESSY VSR will enable time-resolved studies down to the picosecond time scale. The conceptual and technical design report of the

new soft X-ray facility (BESSY III) based on the MBA technology will be realized until the end of PoF IV.

- **DALI**
  DALI, the Dresden Advanced Light Infrastructure 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 this facility will be the application of extremely intense pulsed – and with regard to repetition rate, bandwidth, polarization, pulse form and pulse delays – flexible radiation in the IR to THz spectral range, in materials and life sciences. The experimental stations will thereby have in parallel access to high-performance laser beams and pulsed magnetic fields, thus facilitating unique sample environments. A Conceptual Design Report 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 the European XFEL, a concept is to be worked out to increase the pulse repetition rate up to a CW operating mode.

- **PETRA IV**
  In order to keep the PETRA III research facility on a world-leading level, it is absolutely necessary to upgrade the storage ring to the so-called multi-bend achromat technology. The pre-design 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 Conceptual Design Report will be completed in 2019, the Technical Design Report by 2020. Construction of the critical parts of the new storage ring should start in 2022; the implementation of the storage ring into existing tunnel is foreseen between 2024 and 2027 with a dark period of 2 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**
  This international project will be built up in the coming years under the leading participation of DESY. CTA will be operated as the first research infrastructure in astroparticle physics as an open observatory, combined with the research and data center DESY Zeuthen.

- **ESS**
  Since 2014, the most powerful neutron source in the world is being built in Lund, Sweden, with a strong German contribution. Currently, 15 instruments are constructed by European consortia. German partners (FZJ, HZG, TUM) participate in seven of these projects, with a leading role in six of them. The hot commissioning for some of the instruments begins 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 technology and project development and – in close coordination with national and international partners – work on the realization of this project.

Technical design reports and visibility studies of possible future facilities

- **IAXO**

The “International Axion Observatory” (IAXO) will be the first “medium-scale experiment” for the search of new and very light elementary particles – the so-called axions and axion-like particles. These particles are candidates for the dark matter, its emission from the sun would be traceable with IAXO. Because of its existing infrastructure, DESY is an ideal location for this planned experiment. Until 2020, a Technical Design Report will therefore be brought to completion and a first demonstrator experiment could already be tested.

- **HBS prototype**
  Part of the neutron strategy is the development and implementation of compact accelerator-operated neutron sources which by optimization of brilliance will allow experiments complementary to ESS, ILL and other sources. The HBS type sources will have a broad application spectrum due to its scalability. This novel concept is to be confirmed by a prototype. The Conceptual Design Report of the full scale facility will be finalized within 2019 and followed by a detailed technical report.

- **Global Cosmic Ray Observatory**
  If the Auger Observatory, with the help of the AugerPrime upgrade, will find clear indications of the position of sources of the extremely energy-rich cosmic radiation, the Global Cosmic Ray Observatory (GCOS) should be envisaged for a thoroughly 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 tons of liquid xenon will be developed in international cooperation. A realization could be possible by the end of the PoF IV period (KIT).

2.4 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, and Tier-1 GridKa and Tier-2 centers). From these data, complex algorithms generate new knowledge about the microcosm. Because of its enormous scientific spectrum, our large-scale facilities pose unique challenges on data management and analysis; from high data rates in the real-time analysis systems, complex big data analysis methods and algorithms up to data management for heterogeneous international research groups. New advanced high-speed megapixel detectors will create in future enormous challenges in online visualization, data storage and processing.

The centers of the research field have taken measures to address these challenges, including a new program topic “Data management and analysis (DMA)” in the program “Matter and Technologies” bundling the data and computing competences of Matter. DMA will host the new Interdisciplinary Data Analysis Facility at DESY which is an extension of Tier-2 center to also serve the new large scale photon science facilities like XFEL and PETRA IV. DMA will create a close link to the new research field Information.

Furthermore, Matter is participating in two new graduate schools DASHH (Hamburg) and HEIBRIDS (Berlin) devoted to the training of a next scientists’ generation. The training modules include algorithm developments, machine learning, or real-time visualizations schemes.

3 FUTURE THEMATIC AND PROGRAMMATIC POSITIONING OF THE RESEARCH FIELD MATTER

At the beginning of the Funding Period 2015-2020 (POF III) the research field has adopted a modern and trend-setting program structure, which is based on a close cooperation between the centers and building 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 re-tailored, following the strategy of the research field to respond to the upcoming challenges.

3.1 Overview of the research field Matter in PoF IV

Figure 2 shows the structure of the research field Matter with its programs, its topics and LK II infrastructures. (LK I refers to research, LK II refers to user facilities.)

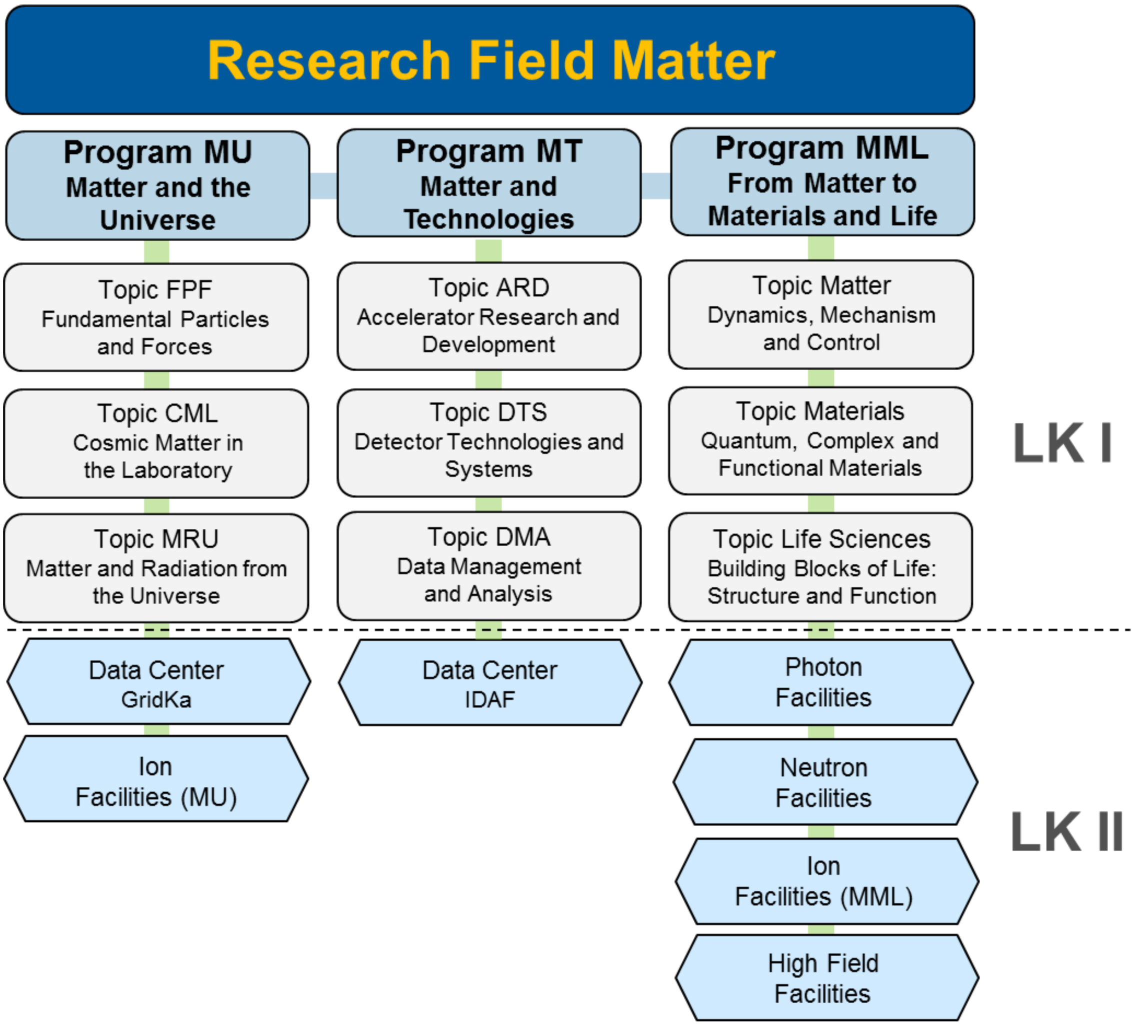


Figure 2: Program structure of the research field Matter for PoF IV (2021-2027).

Several structural changes within the research field Matter (see Tab. 1) are planned for the new PoF Period starting 2021:

In the MU program, the topic structure remains unchanged; in 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 research topics were bundled more strongly to adapt to the future challenges. The one POF III research topic, consisting of five research themes, will be replaced by three research topics. In addition, the LK II infrastructures of GSI will again contribute to the MML Facility Topic “Ion facilities**”**.

In the MT program a new program topic “**Data management and analysis**” (DMA) will be implemented. DMA will concentrate research, competence and resources in scientific and data-intensive computing over all Matter. 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 Matter. It will provide strong interfaces to the new research field Information and the Helmholtz Incubator as well as national and European developments. Although DMA can built up on strong support and expertise by the Helmholtz centers involved, it will need additional resources to leverage the full potential of DMA all across Matter. The definition of the other two topics in MT, Accelerator Research and Development and Detector Technologies and Systems, will not change fundamentally.

The scope of the Tier-2 center at DESY will be extended and the center will be renamed the "**Interdisciplinary Analysis Facility**" (IDAF). Keeping the obligations to the LHC experiments the IDAF will be in addition extensively used for the scientific analysis of research with photons, accelerator research and astroparticle physics. The IDAF will be transferred to the program MT.

Table 1: Overview of structural changes in the research field Matter for the PoF IV period 2021-2027.

Structural Changes of Research Field Matter	Involved Research Fields	Involved Programs	Involved Topics	Involved Centers
Introduction of new topic **DMA**	Matter	MT	DMA	DESY, FZJ, GSI, HZDR, HZB, HZG
Transfer of **TIER-2 data center** from program MU to MT (new name: **IDAF**)	Matter	MU, MT	---	DESY
Transfer of the **Biophysics Department** at GSI from RF Health to RF Matter	Health, Matter	MML	Life	GSI
Transfer of research activities on **magnetohydrodynamics** at HZDR from RF Energy to RF Matter	Energy, Matter	MML	Matter	HZDR
Transfer of the research activities on plasma physics at **IPP** from RF Energy to RF Matter	Energy, Matter	MU	MRU	IPP
Transfer of **IKP** from FZJ to GSI within the RF Matter	Matter	MU, MT	CML, ARD, 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 Matter of the program MML is HZDR's research on **Magnetohydrodynamics** (MHD), based on a world-wide 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, for example, mass accretion on protostars or black holes by the magnetorotational instability. 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 HGF, specific fundamental research activities in plasma astrophysics and astroparticle physics of the **Max-Planck-Institut für Plasmaphysik (IPP)** at Garching und 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 und MT.

The activities of the FZJ **Institut für Kernphysik IKP** (except IKP-3) in the field of hadron and fundamental physics will be transferred to GSI, thereby preserving the specific competences of the

IKP and its close cooperation with RWTH Aachen. The focus of the transferred IKP institutes will remain on the construction of the HESR storage ring and major contributions to the PANDA experiment at FAIR. In addition, the IKP-2 is developing methods for measuring electric dipole moments of charged particles and participating in neutrino experiments. The Jülich competences will continue to be available to the program MU as well as MT.

Overall, cooperation across the programs of the research field Matter as well with other research fields will be further intensified.

Several facilities and activities will phase out in the next years in order to enable a new programmatic positioning of the research field Matter in the future:

- MU (DESY): The ILC preparatory project will be reduced. The resources released will be transferred and used to strengthen the new topic DMA.
- MU (GSI/FAIR): The major focus of GSI will be the completion and commissioning of the FAIR facility. In parallel a limited LKI and LKII intermediate research program, called FAIR phase-0, will be pursued at the GSI accelerators.
- MU (GSI/FAIR): With the installation of the new experimental setups at the FAIR facility starting in 2023/24, the majority of the experiments at GSI will be phased and relocated to the respective FAIR experimental stations.
- MU (KIT): The Dark Matter Experiment EDELWEISS will phase out in 2019. KIT contribution to EDELWEISS was already reduced during the last years. In term, KIT builds up its participation in DARWIN.
- MU (KIT): KASCADE Grande has ‘mission accomplished’: 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, which has been developed significantly with KASCADE Grande, will now enter the next generation of projects, e.g. IceCube-Gen2.
- MT (DESY): The DESY-MPG collaboration project REGAE will be completed in 2020. The resources released will be allocated to the operation of the SINBAD/ATHENA research infrastructure.
- MT (HZDR): Development of radiation-hard gas detectors will stop until end of PoF III after successful prototype implementation and transfer of technology to interested centers for application.
- MT (HZDR): Basic development of detectors, especially for medical applications has been translated to Health for further development and clinical implementation.
- MT (HZDR): HZDR’s Detector laboratory for the development of detectors of the FAIR facility has been closed after prototyping was completed.
- MT (HZDR): Department for theoretical Hadron physics has been re-structured and re-oriented 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 Hamburg.
- MML (DESY): A large upgrade project of the FLASH-Linac with a switch from pulsed operation to continuous (CW) mode is no longer considered. Instead, the development of the CW mode as a long-term upgrade project for the European XFEL and the improvement and implementation of new concepts (e.g. seeding, advanced FEL concepts for shorter wavelengths, (sub-)fs photon pulses) in the FLASH facility within the current configuration of the linear accelerator will be carried out.
- MML (HZB): After more than 25 years of most successful user service, the BER II reactor will be taken out of operation by the end of 2019. In order to preserve the competitive instruments for the neutron scattering community, HZB is committed to transfer these instruments and the related expertise to other neutron sources in Germany, Europe and worldwide.
- MML (HZDR): Research on ODS-steels for non-nuclear applications will phase 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 expires by the end of PoF III and resources will be focused on the contribution to ESS.
- MML (KIT): Since 2015, there has been a transition of the Synchrotron Radiation Source „Angströmquelle Karlsruhe (ANKA)“ from a user facility (LK II) to the Karlsruhe Research Accelerator (KARA) (LK I). KARA – as part of the Karlsruhe Accelerator Technology Platform (ATP) – is essential for the Program MT, Topic „Accelerator Research and Development“ (ARD). At KARA, KIT develops and tests novel concepts for accelerator physics and the use of synchrotron radiation.

3.2 Positioning of the Programs

Program *Matter and the Universe* (MU)

With state-of-the-art theoretical and experimental methods, this program addresses the basic correlations of the fundamental building blocks of matter and their interaction and the complex behavior of hadronic matter the influence of elementary particles on the evolution of our universe. With the competences in the Helmholtz Centers DESY, GSI, FZJ[2], 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 elementary 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 its mass. Our view, however, is still incomplete and partly inconsistent. To answer the many unresolved questions, the MU program is organized around three topics which are thematically and methodically connected to each other.

Topic *Fundamental Particles and Forces (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 interaction, *ii*) Search for new particles and phenomena, and *iii*) Cosmology and dark matter. Prominent instruments are the ATLAS and CMS experiments at the Large Hadron collider of CERN and also the Belle/Belle II experiment to investigate electron-proton collisions at KEK in Japan. 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 the search for CP violation via EDMs and neutrino oscillations – are also closely related to this topic.

Topic *Cosmic Matter in the Laboratory (CML)* (GSI)

In this topic – at GSI, CERN, and further accelerator facilities, and later at FAIR – we explore the complex and exotic forms of matter, which are generated by the strong interaction (QCD) and which played a crucial role for the dynamics of the early universe and the evolution of many astrophysical objects. We will investigate the complexity of matter at all length scales, from the structure

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[2]The competences of the corresponding research units at FZJ relevant for the programs MU, MT and FAIR are planned to be transferred to GSI in PoF IV.

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, and 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 the 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 MML program).

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

In this topic we investigate the generation, acceleration and the 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 multi-messenger view of the universe at high energies. The 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 its role as a possible particle of dark matter, and also in future projects we will contribute our competences in 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 is 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 MML and MT programs.

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 research 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 Matter and Technologies program. With the MT program, the centers DESY, FZJ, GSI, HZB, HZG, HZDR and KIT – through intensive and coordinated cooperation between the centers participating in MT and with other programs of the research field Matter – are laying the foundation for speeding up and optimally use the technological progress. This procedure attracted interest and imitation worldwide. In the new funding period we will bundle the efforts in the field of data – data taking, recording and processing – in a new topic. This topic as well as the remaining part of MT is closely networked with the two other Matter programs.

Topic *Accelerator Research and Development (ARD)* (DESY, GSI, HZDR, HZB, KIT)

In this area, we will develop concepts and methods in the next years to extend the possibilities of conventional accelerator systems beyond the 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 in the field of superconducting CW accelerators and extremely brilliant particle sources, advanced concepts for beam control, dynamics and diagnosis, but also for the development of new methods and prototypes. Particular attention will be devoted to the development of novel plasma accelerator technologies which will allow by orders of magnitude more compact structures as it is now possible with conventional accelerators. The goal of the program 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 (DTS)* (DESY, GSI, KIT)

We see a great potential in the development in the field of highly granular, pixelated detector systems. The main challenge will be to keep pace with the 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, we see a major opportunity in the intensive development of mixed optical and electronic systems.

But we also see important applications for other technologies 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 which require an extremely low noise level.

For the development of modern detectors, test facilities are essential. Thus, the DESY test beam plays an important role.

We see a considerable synergy potential in an even closer cooperation among the various centers. In order to facilitate this, we developed the concept of “Distributed Detector Laboratory” (DDL). In it, we want to pool competences throughout Germany into Helmholtz and simplify the utilization also across center borders. A close integration of universities into this structure is a key concern to us.

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

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, which 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 Matter 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 which 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 for 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, there will be a close cooperation with users and scientists from all Matter programs such that goals and solutions will be deduced from this cooperation. The new topic will encompass the treatment of data management and fast data-taking with full integration of the user, 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 handling and analysis of large amounts of highly complex data being produced at ever increasing rates is a challenge across research fields. The new DMA topic 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 3.3) and the Helmholtz Incubator process. The DMA topic 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 closely cooperate on many levels, ARD and DTS are closely linked through the development of advanced accelerator concepts, powerful control systems, detectors for beam diagnostics and powerful readout systems. The new DMA topic deals with topics which are of major relevance to all MT topics as well as to the other Matter programs, as the handling and analysis of large amounts of data from accelerator facilities, experiments and simulations. In our program, we will extend, promote and structurally secure this close cooperation.

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

In this program 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 with the targeted use of the analytical potential of the large-scale facilities belonging to the research field. In the focus are complex materials structures, materials under extreme conditions and also quantum and nano-structures and biological structures. The research program encompasses fundamental questions of condensed matter, application-oriented research projects in the materials analysis for the development of new technologies up to cooperation projects with industry (see chapter 3.3).

We expect completely novel experimental possibilities and revolutionary new insights from the experimental stations of the X-ray laser European XFEL which should have taken up routine operation at the beginning of the next period of funding.

This program includes the LK II user operation of the large-scale facilities. Here, all organizations of the science system, particularly universities, are participating. The stable operation, the professional maintenance on site and the dedicated measurement setups allow the utilization of the analytics for miscellaneous scientific disciplines and for a broad national and international user community. The research field Matter also closely cooperates with neighboring research fields of the Helmholtz Association.

We reorganized the structure of the program topics to be able to cope with the future challenges as effectively as possible: The PoF III program topic “In-House Research on the Structure, Dynamics, and Function of Matter”, which consists of five “research themes”, will be replaced by three new program topics which are illustrated hereafter.

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

In this program topic, the focus is on fundamental aspects of structure and dynamics of complex matter. With this, we want to gain a deeper understanding of the mechanisms underlying the properties of matter and mainly use this to exercise a targeted control of these properties on a microscopic level and on ultra-short time scales. In this context, we for example will investigate the behavior of matter in electromagnetic fields which 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 topic of our research. Another central challenge we will face is the observation and manipulation in real-time of molecular reaction paths on the atomic level. Eventually, we will extend the control of microscopical 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* (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 at nano-materials 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* (DESY, GSI, HZB, HZG, KIT)

The topic aims at understanding the building blocks and processes of life, from the molecules up to organisms. Therefore, we elucidate, by developing and employing MML-specific tools and techniques, structure, dynamics and function of components on various hierarchical levels. On subcellular 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 their mediation of cellular processes. On higher hierarchic levels, we study morphology & morphodynamics of cells, tissues, organs up to small organisms. Combining molecular and organismal strategies, we analyse 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); in Ecology (biodiversity), in bionics and others.

LK II facilities

Within the coming program period PoF IV the MML program will be significantly influenced by the internationally positioned large-scale facilities European XFEL (Hamburg), FAIR (Darmstadt) and ESS (Lund). The European XFEL has already taken up operation in 2017 and within the framework of PoF IV, it is important to completely exploit the enormous potential of this facility in its experiments. FAIR will be commissioned in 2024/2025, whereas the start of user-operation at the ESS is planned for 2023. The Helmholtz Centers are centrally involved in the construction, operation and further development of the instrumentation.

Photon facilities: The investigation of matter at the highly brilliant synchrotron radiation sources BESSY II / BESSY VSR and PETRA III as well as at the free-electron laser facilities FLASH and European XFEL, in a very broad scope of application enable 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 are organized by the user platforms “Jülich Center for Neutron Science” JCNS (FZJ) and “German Engineering Material Science Center” GEMS-n (HZG). A key role is played by the Heinz Maier-Leibnitz Zentrum MLZ, a renowned national user facility of European importance. 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 of 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 storage-cooler facilities HITRAP, CRYRING and ESR, the KJ/PW laser PHELIX, experimental areas at UNILAC and SIS18 for atomic physics, laser + 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: They enable the investigation of matter in the highest electromagnetic fields, as available in the form of ultra-high magnet fields of the Dresden High Magnetic Field Laboratory (HLD) and through highly intensive photon pulses at accelerator-based infrared and terahertz sources (ELBE) and the high power laser systems DRACO and PENELOPE (HZDR), PHELIX (GSI) and HIBEF, coupled with the brilliant X-rays at the European XFEL.

3.3 Cross-Cutting Activities

The programs of the research field Matter are closely interconnected with regard to science, personnel and institutions. The tripartite program allocation into MU, MT and MML has already proved very successful for the concentration on key questions.

The programs of the research field are interdisciplinary and to a vast extent positioned across the centers. Here, we see the breeding ground for new cross-program initiatives and projects within the phase of a funding period, which we will promote more strongly in the future. In addition, there are scientific challenges which need cooperation across research fields. In this case, the research field particularly identified structural biology, radiation research, materials science, quantum technologies and the future challenges in data management and in the analysis of large amounts of data.

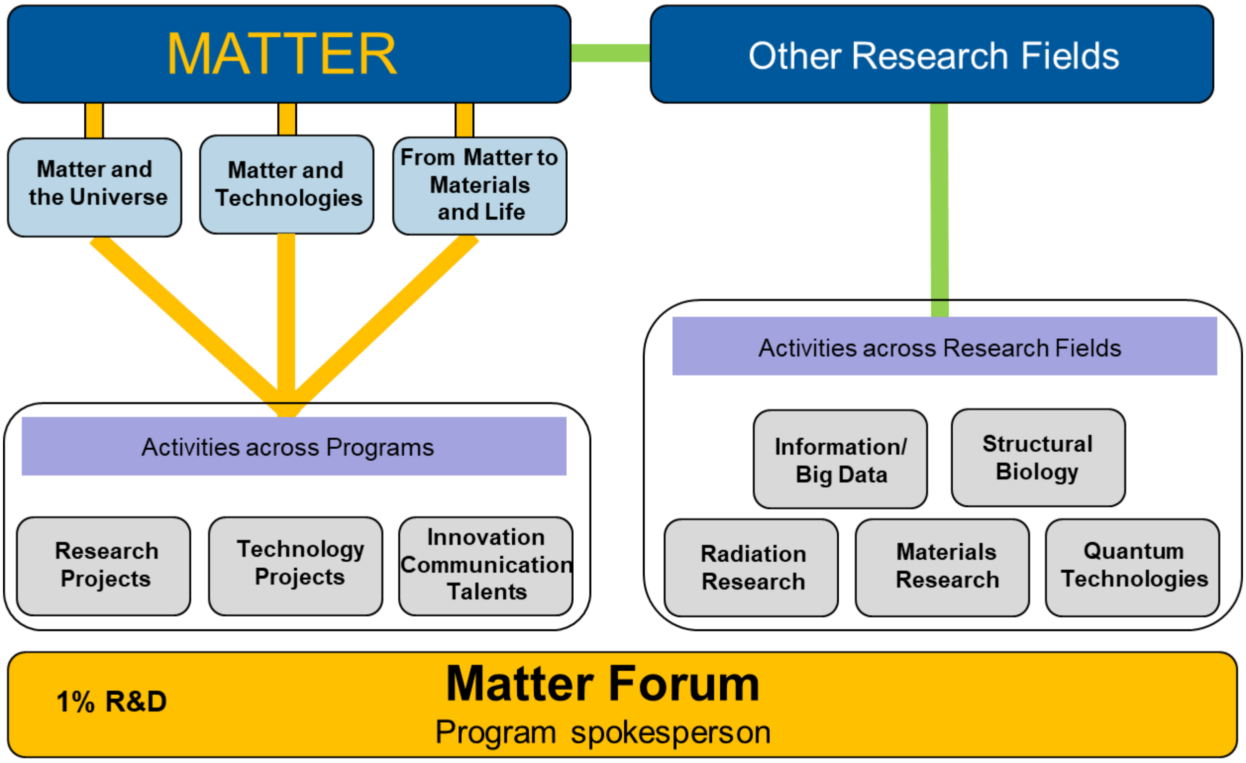

Figure 3: Structure and function of the Matter Forum.

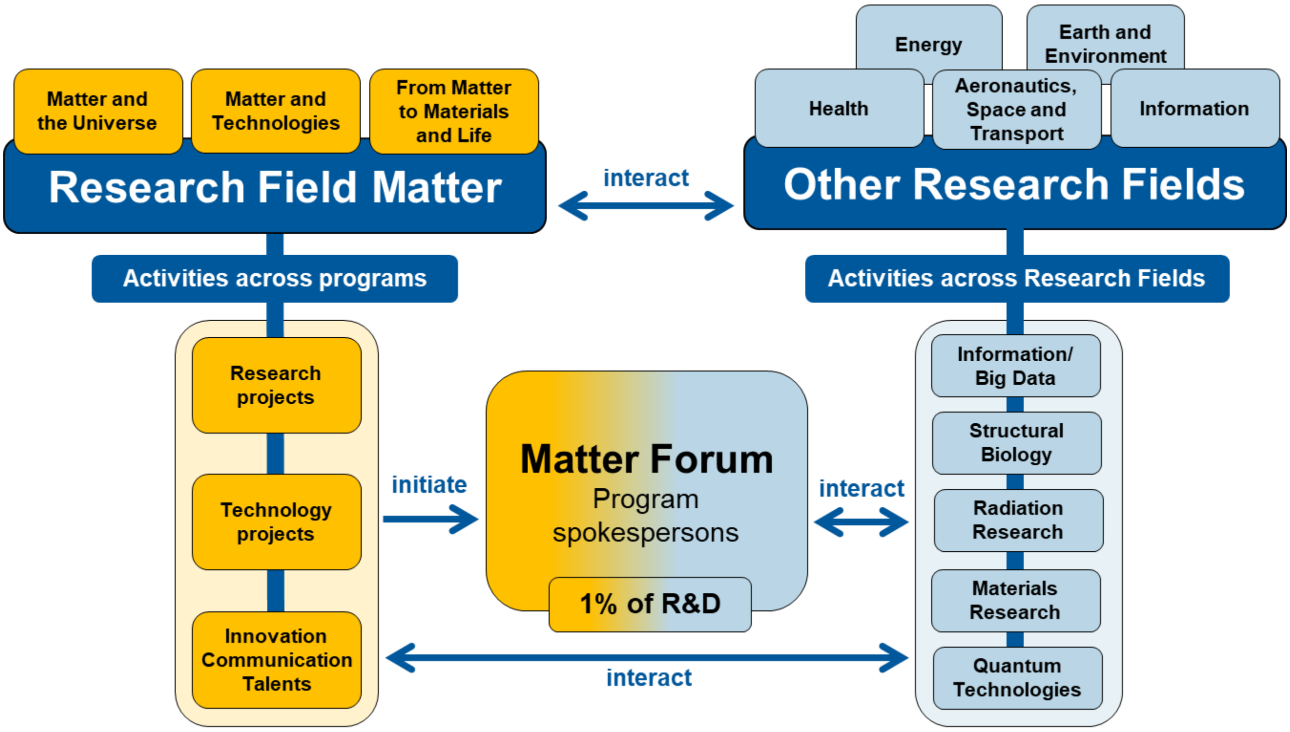

Figure 4: Structure and function of the Matter Forum.

Therefore, the research field will implement a new “Matter Forum” which in the future will initiate, coordinate and fund activities across programs and research fields (see figure 3). The research field Matter assumes that the other research fields will implement complementary structures.

The Matter Forum is a new structure of the research field to elaborate initiatives in research, in technology development, and in innovation, talent management and communication, and it submits proposals for new initiatives to the management board for implementation. For this purpose, each research center allocates one percent of its LK I[3] budget. The funds of a center are retrieved in case a center will participate in a Cross-Cutting Activity.

The Matter Forum is managed by the three program spokespersons. At regular intervals, they trigger the collection of new ideas, for example, by organizing workshops (“Matter Marketplace of Ideas”). Proponents of new ideas are asked to prepare short project proposals in written form which are first presented to the management board and then to the research field platform. The Matter Forum particularly encourages junior scientists to engage in interdisciplinary cooperation.

Activities across programs

The Matter Forum should be open to all kinds of topics and allow both, new cross-program research and technology projects and research field initiatives in the areas of innovation, talent management and communication.

Research projects: This typically includes 1 to 3-year projects which are visibly drawing on the competences of the three programs. *Precision Physics at Low Energy* was identified as a particu-

[3]LK I: Research

larly rewarding field to be increasingly investigated in experiment and theory in a joint effort. A few examples are: Effective field theory, quantum criticality, light-matter interaction, physics of stellar plasmas, many-particle and spin systems, extensive air showers of cosmic rays. Another field of topics is *New Methods of Theoretical Physics*. Past experience has shown that the exchange between different physics disciplines leads to new and partly revolutionary insights.

Technology projects: We aim to particularly initiate technology developments which are essential for the advancement of research infrastructures of the Research Field Matter. We expect innovative proposals especially from the MT program which is inherently cross-program-oriented. Examples hereof are plasma acceleration and novel data management concepts. Here, it will be decisive that this Research Field reacts in a flexible way to international developments and attempts new concepts.

Innovation, communication and talent management: The large research infrastructures are an elementary part of the research field. On the one hand, they provide an enormous potential for cooperation with industry; on the other hand, it needs an intensified communication with society which has the right to understand the social value of these large investments. Thus, explicitly in the research field Matter, the innovation and communication aspects are a common challenge of all participating centers.

The perspectives of the research field in the area of *Innovation and Technology Transfer* are outlined in chapter 3.6. The joint activities in this area should be coordinated and funded in the Matter Forum.

In the field of *Communication and participation* the Matter Forum will conceptualize and implement new cross-center formats of interaction with the society in addition to the already existing activities within the centers.

The research field Matter offers unique opportunities for the training of the next generation of scientists and engineers. Furthermore, *Talent management* is a major concern of all participating centers (see chapter 3.7.).

Activities across research fields

Connections exist to other research areas in multiple ways – through people, common projects, or shared methods. Several topics have been identified request cooperation across research fields.

Information/Big Data

Data handling of the research field Matter manifests several marked features. The particularities are based on the amount and complexity of the data and the rate at which the data are produced. This brings about great challenges for networking, analysis, modelling and sustainable storage.

The research field, in close cooperation between all participants, thus developed a strategy to advance the research on *Information and Data Science* by taking into account measures of the Helmholtz Association as well as national and European funding programs and to provide optimal technologies and infrastructures to research groups.

A core element of this strategy is the setup of a new topic within the research field, located in the Matter and Technologies program. As outlined in chapter 2.3, the new topic DMA will bundle the competences from the different fields in Matter, which deal with management and analysis of enormous amounts of data with the help of up-to-date methods. A central task of this topic will be to closely involve the expert scientists in Matter to secure the links to relevant activities in the research field Information. This is done to achieve both, the networking of groups which develop their own competences in these fields and the propagation of improved methods for modelling, analysis and data management within the scientific discipline in Matter.

Because of the clear internationality, we strongly engage in European projects, e. g. in "Indigo Data Cloud" (DESY, KIT), European Open Science Cloud (DESY, FZJ, KIT), EUCALL (DESY, HZDR, European XFEL) and will expand this engagement. It is part of the strategy to play a prominent role on the issue of data also in the current and coming bids of the European Commission; on the one hand to lead the developments in terms of the important issues for research in the research field Matter and on the other hand to provide developed solutions to others, extending beyond Helmholtz.

Structural biology and biological processes

The detailed molecular understanding of biological processes and the function of involved molecules is elementary for many areas of life sciences, bio-medicine and pharmacology. The basic prerequisite is the decoding of the three-dimensional structure and dynamics of molecular building blocks. Macromolecular crystallography with synchrotron radiation plays a key role here. With the powerful X-ray lasers which are now available (particularly the X-ray laser European XFEL in Hamburg), revolutionary new possibilities are presented to determine both, the structure of macromolecules in nano-crystals and the very fast dynamics down to the femtosecond range with simultaneous atomic resolution. Very specific structural information as hydrogen bridge bonds can be obtained with nano-crystallography. By means of X-ray and neutron small-angle scattering, it is possible to study the dynamics of macromolecules in solution under nearly physiological conditions. Only recently, the cryo-electron microscopy turned into a key method for structural analysis of large macromolecular complexes and is available for Cross-Cutting Activities within the framework of the new interdisciplinary Center for Structural Systems Biology (CSSB). In addition, the NMR spectroscopy enables unique insights into the dynamics of biological macromolecules and is an important instrument in the structure-based development of new medication.

In this cross-research field activity, a competence network will be established which optimally exploits synergies between structural biology activities within the research fields Health, and Key Technologies, which facilitate expertise and also give access to nuclear magnetic resonance (NMR) technology in the centers HMU, KIT and FZJ, and the research field Matter, which offers methods and expertise for research with synchrotron, FEL, neutron and ion radiation including highest fields.

An important future pillar will be CSSB at DESY, with ten institutions – among them the three Helmholtz centers HZI, FZJ and DESY – cooperating in the field of structural biology aspects in infection research. With the X-ray sources PETRA III and BESSY II, the free-electron laser FLASH, and with the participation in and with carrying out experiments at the European XFEL, the neutron sources FRM II/MLZ and ESS, the research field Matter is in an outstanding position to render decisive contributions to these activities across research fields.

Radiation Research

Radiation research, based on large-scale infrastructures, is very prominent within the Helmholtz Association and covers both radiation protection and therapy with an emphasis on “novel” types of radiation such as high-energy heavy ions and ultra-short pulsed beams (laser-driven accelerators). For this very reason, the Cross-Cutting Activity “Radiation Research” has been created at the beginning of PoF III in 2015, comprising the research fields Energy and Health (plus a participation of DLR since 2016). In PoF IV, with the transfer of the Biophysics department at GSI from Health to Matter, the research field Matter will participate in addition. The main goal is to identify areas of common interest and the potential synergy, as well as to tap this potential for the future. The newly found Cross-Cutting Activity addresses the three major topics of radiation research, namely: 1. radiation biology and radiation protection, 2. radiation ecology, and 3. radiotherapy and molecular imaging.

The main topics of research within this activity are:

- identification and quantification of long-term benefits and risks to health from medical, environmental and technological exposures;
- accurate determination of the actual exposures (dose and radiation effect) in different radiation environments (households, workplaces, clinics, space);

- development of technological and application-based solutions to keep the doses as low as reasonably achievable;
- development of strategies to minimize potential risks to humans and environment from decommissioning and long-term deposition of nuclear waste;
- optimization and novel concepts in radiotherapy.

The research field Matter will play a key role in this Cross-Cutting Activity, with contributions in particle radiobiology and medical physics. The field Matter will interact with other research fields. The details of the overall research program are currently under definition and will soon lead to a renewed and stronger structure for the collaboration.

Materials Research

There is a joint effort of the research fields Information, Matter and Energy on materials research. Together, the research fields will develop a comprehensive Helmholtz materials research strategy that systematically builds on their complementary competences and unique selling points in relation to the Helmholtz mission and combines the special scientific possibilities of the centers with application perspectives. The definition and description of interfaces in the sense of synergies between the individual research fields will be presented in this comprehensive Helmholtz materials research strategy.

The main pillars of materials research in 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;
- the development of new systemic approaches in materials research based on the possibilities of digitization, 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 research field Matter contributes with its unique large-scale facilities to address interdisciplinary questions on characterization, modification and synthesis of materials for a deeper, microscopic understanding of matter, materials and biological systems and thus supports also application-oriented materials research.

Quantum Technologies

Research in quantum technologies within the Helmholtz Association encompasses a broad spectrum of activities ranging from fundamental studies of quantum phenomena to the design of components, prototypes and systems. The Helmholtz association has identified five areas of cooperation within Helmholtz centers:

- Quantum Computing
- Quantum Communication
- Quantum Sensors
- Quantum Material
- Simulation und Numerical Methods

The research field Matter is carrying out research in quantum computing, quantum materials and quantum simulation and cooperates in all 5 areas with other research fields. One main focus is the targeted use of the high-end large-scale facilities of the research field.

3.4 Research infrastructures and roadmaps

For the mission and the research objectives of the research field Matter, large-scale facilities and their advancement play an important role. Therefore, the national roadmap for research infrastructures is an important instrument for the research field to carry out long-term strategic planning.

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

In the funding period PoF IV, BESSY VSR will take up operation and Technical Design Reports 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. The LENS initiative will link the national to the European strategies. With the end of operation of the research reactor BER II, the Helmholtz centers FZJ and HZG will organize the German participation at the European spallation source ESS in Lund, which will take up user operation in 2023. The development of compact accelerator-driven neutron sources at FZJ aims at securing the user base for research with neutrons.

The international Facility for Antiproton and Ion Research (FAIR) in Darmstadt is to be completed in 2025 and will 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, materials research, as well as biophysical radiation research and ion beam therapy and space radiation research in close collaboration with ESA.

The next update of the CERN strategy is ongoing during 2019/2020. The European strategy for astroparticle physics from the year of 2010, coordinated by APPEC, was updated in 2017. In the field of particle and astroparticle physics, the paramount projects are the detector upgrades for the high-luminosity phase of the LHC and the construction of the international Cherenkov Telescope Array (CTA). The Belle II experiment in Japan will go into operation for research and within the period of PoF IV, the KATRIN spectrometer will measure the neutrino mass in regular operation with tritium run. The Auger observatory uses the current *AugerPrime* upgrade for mass determination and the search for cosmic ray sources until 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.

3.5 Strategies of cooperation

The centers of the research field Matter closely cooperate with German universities and other national and international partners. Thus, several partner centers participate in the already running strategic development investment initiatives LHC upgrade, Helmholtz Data Federation (HDF), the distributed infrastructure ATHENA and in the proposed distributed infrastructure DDL, including university groups as partners. Cooperation with universities is mostly carried out within scientific collaborations and user operation, and also 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 by many different collaborations in the past years, for example by the Helmholtz Institutes in Jena and Mainz, and also by strategic cooperation agreements and projects with selected universities, partly accompanied by excellence programs of the federal states. These networking and cooperation activities must be further strengthened in the coming years. A main focus is on the next excellence initiative of the federal government and the federal states in which all centers of the research field will act as partners of the applying local universities.

Moreover, the programs play an essential role as talent factories for junior scientists in these complex technology- and science-oriented surroundings, but also for attracting and training engaged and motivated technicians and engineers.

3.6 Transfer of knowledge and technology

The activities of our research field offer a high innovation potential. Particularly in view of large-scale facilities and the associated technologies, the research field Matter is a central driver of innovation in the Helmholtz Association. Therefore, we see technology transfer and innovation support as an important part of the strategy.

On the one hand, this is a matter of technology transfer and on the other hand of knowledge transfer which is also a central transfer element of the centers within the research field Matter. In the field of innovation and technology transfer, the focus is on three core areas: supply-oriented transfer, demand-oriented transfer and company start-ups. Supply-oriented transfer means the exploitation of science-driven technology developments for short-term and also commercial use. The research field will ensure that the numerous innovation potentials will be used in the centers and also validated at the end. For the validation of developments, it is necessary to cooperate with industry at an early stage in order to include the requirements and the know-how of industry from the beginning. With demand-oriented transfer, the Helmholtz Association assumes the role of a service provider for industry. Particularly the large-scale facilities but also complex instruments and methods are usable for industry and are further optimized for industrial use. There are different approaches in the centers on how to organize such a role. An important element can be the appointment of “Industrial Liaison Officers” (ILO), with the aim to carry out services oriented at the demands of industry. ILOs are scientists who as experts execute measurements and analyses for industry. Moreover, especially established limited companies (GmbHs) may help to offer services within a secure legal environment. Furthermore, there is an increasing number of start-ups organizing the link between industry and research center. Finally, it is a major concern of the research field to facilitate start-ups out of the centers. This special kind of exploitation represents a challenge within the high-technology environment of the research field; nevertheless it is to be strengthened.

Even when exploitation and transfer are largely organized at the centers; on the level of the research field, the association can make a substantial contribution to increase the utilization of the innovation potential. We want the research field Matter to become an innovation area in which the utilization of synergies is organized and experienced. It is of major concern to us to present ourselves as strong partners for industry and commerce, in order to allow the efficient transfer of innovation into society. The goal is to establish an innovation platform within the research field which promotes a stronger networking and a marked exchange of information between the centers. Conceivable are also regular meetings of the ILOs to exchange experiences and to optimize processes and procedures. In the longer term, individual service elements of technology transfer may be concentrated at individual locations, thus avoiding large parallel structures.

In the field of knowledge transfer, the research field Matter particularly sees its task in ensuring that the scientific activities have a wide-spread impact on society. It is not exclusively information about the activities and priorities of the research field. The point is rather the effect that these activities have on all areas of society. An important element is the socio-economic influence of the large-scale facilities and the projects of the research field. You can find researchers, technicians, engineers and mechanics working in numerous firms and environments all over the world who went through vocational training just in this field. Last but not least, the fascinating infrastructures of the Matter centers already encourage pupils to think about taking up a technical or scientific education or study. Important is also the contribution of the centers to cross-cultural collaboration. Understanding and tolerance towards other cultures is a central element of scientific work. Particularly nowadays, this impact on society must not be underestimated.

3.7 Talent management

The performance and scientific success of our research field depends to a decisive extent on talented employees. At the same time there is the challenge of competition with international research institutes, universities and industry in the search for talents and proven experts.

The large-scale facilities of the research field allow internationally competitive research. They are high-tech platforms attracting scientists from all over the world and offering a unique interdisciplinary environment to junior scientists. With the globally attractive large-scale facilities and transparent career pathways, the research field and its centers position themselves as international competitors for the best talents. On this basis, we will intensify our international recruitment activities on all levels and we will specifically apply the measures developed at community level to recruit ambitious scientists with a great potential for the future.

While the career development of junior scientists is already established to a great extent; in the future, we increasingly want to move into focus employees from the technology (particularly IT) and the administrative sector. For this aim, tailored target group measures of the Helmholtz Association will be used (e. g. existing doctoral programs or the President's new career development initiative for postdocs), and research field and center-specific structural measures will be developed as well. This will be carried out in close cooperation with selected strategic partners, for example with local universities. Moreover, the preparation for a career outside of science will gain importance.

The guarantee of equal opportunities for women and men is an essential prerequisite for strategic talent management. The research field and its centers thus developed various measures to reconcile work and family life, which then are combined to an individually applicable solution. These measures particularly include the targeted support of women to increase their quota in leading positions.

Basically, talent management is the responsibility of the individual centers; however, if thematically reasonable or required, the research field will furthermore develop measures across the centers (e. g. for recruiting and training of dedicated technicians and engineers), or help shaping measures across research fields (e. g. training of data scientists).

Within the programs, we plan to establish a systematic mentoring program creating the possibility for doctoral candidates and junior scientists to find a mentor at another center. On this basis, we see the potential to establish a cross-center graduate program, with the aim to increase mobility between the centers for junior scientists and to further strengthen networking.