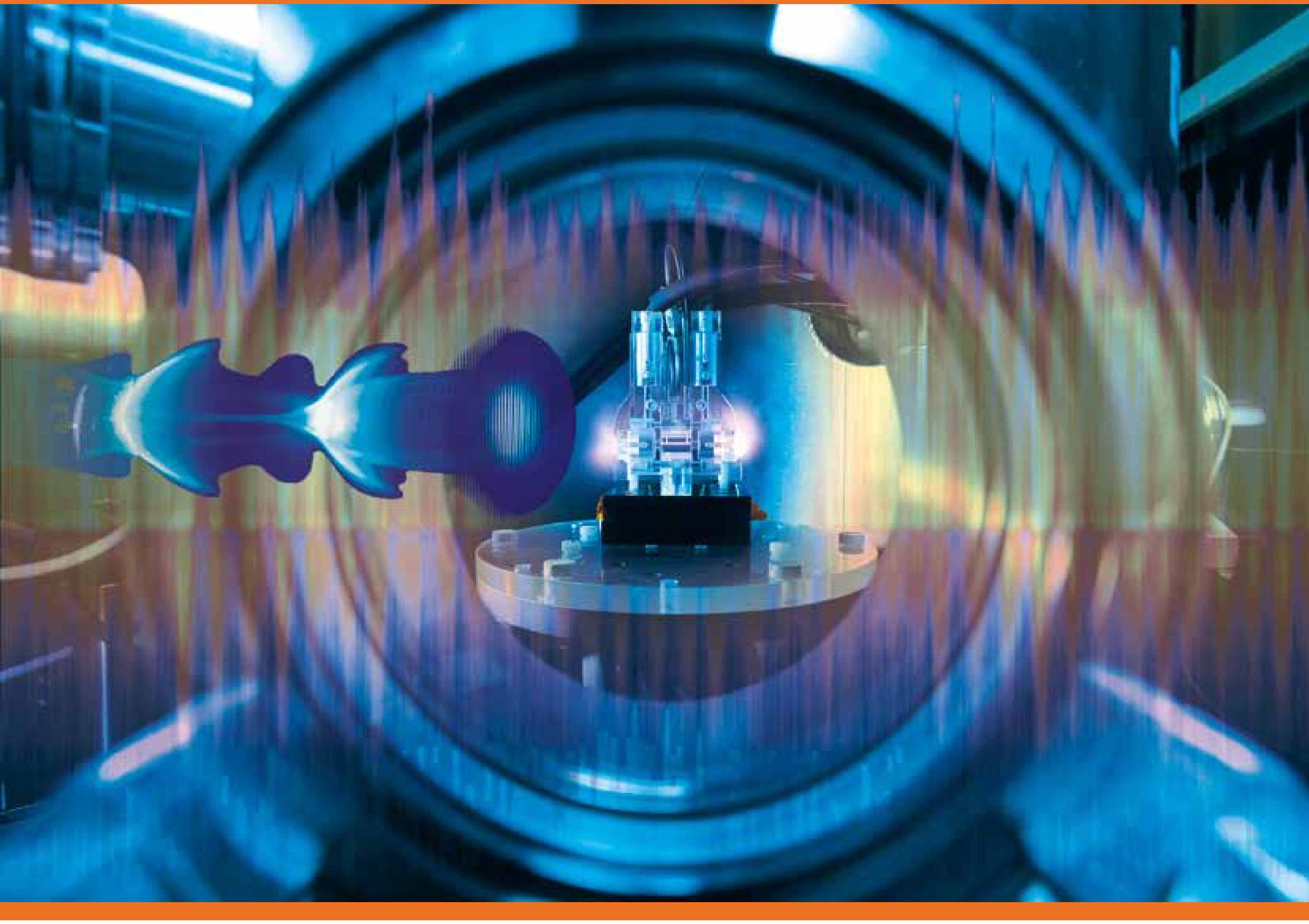
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Proposal for the Helmholtz Research Program

MATTER AND TECHNOLOGIES

Research Field MATTER

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



B. PROGRAM *MATTER AND TECHNOLOGIES*

Spokespersons

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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

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1. OVERVIEW

Matter and Technologies (MT) is a Program in the Research Field *Matter* dedicated to working on key enabling technologies for research in *Matter*. In PoF III, a very ambitious program with two Topics in the area of accelerator (Topic MT-ARD) and detector research (Topic MT-DTS) was established. Many highly visible and promising results were achieved already, as documented in the outcome of the centers' scientific evaluations. To address the rising challenges connected to the handling, processing and understanding of the data produced in the Research Field, MT will be expanded by the Topic *Data Management and Analysis* (MT-DMA) in PoF IV. The new Topic will be supplemented by a powerful data center, the Interdisciplinary Data and Analysis Facility (IDAF), which will grow out of the current Tier-2 center at DESY and become associated to the Program MT as a LK II facility.

A key challenge of the field is the development of powerful and at the same time compact accelerators. Novel acceleration technologies promise significant advances, not only in achievable parameters but also in compactness and in cost. Advancing these technologies to a point where they can be used in a user facility could be a game changer. Nevertheless, established acceleration techniques based on radio frequency (RF) technologies continue to be essential for progress in the field. A highly non-trivial issue remains the need to push all these technologies as far as possible, while at the same time considering that they will need to run in a user facility under real operating conditions.

Another key challenge of the field is the development of excellent detectors. This is closely intertwined with the challenges and opportunities provided by new and powerful accelerators. The field of detector science is rapidly progressing, and MT plays a central role in advancing new technologies in this area. The upcoming large experiments at e.g. the European XFEL, HL-LHC, or FAIR require very advanced detectors with unprecedented performance. Pushing the limits towards what is physically possible will be essential to meet all demands, and thus to enable new scientific results.

Our facilities produce enormous amounts of highly complex data. Extracting knowledge from these data is our third key challenge which requires the most advanced methods from computational and data science. Developing these methods, making them available to all areas of the Research Field *Matter*, and scaling up the software and hardware infrastructures to meet the needs will create unprecedented capabilities to understand the complex systems studied at our facilities.

The challenges in all three Topics of MT require a special effort and strong coordination among the Topics and all the participating centers. Only together can we truly become the enablers and game changers of the future within the Research Field *Matter*.

The Helmholtz centers DESY, FZJ, GSI with the Helmholtz institutes Jena and Mainz, HZB, HZDR, HZG, and KIT collaborate in the Program MT. Close links are maintained to the other Programs in the Research Field *Matter*, *Matter and the Universe* (MU), and *From Matter to Materials and Life* (MML), to other Research Fields, and to other national and international partners. MT thus lays the foundation for the speedy and optimal use of technological progress and provides a stable and forward-looking platform, including a unique suite of test facilities, for aggressive technology development. This approach has attracted great interest and is now being duplicated around the world.

1.1. Planned Resources

The following tables show the costs of the Program MT by Topic and the expected distribution of personnel resources for activities in FTE. 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.

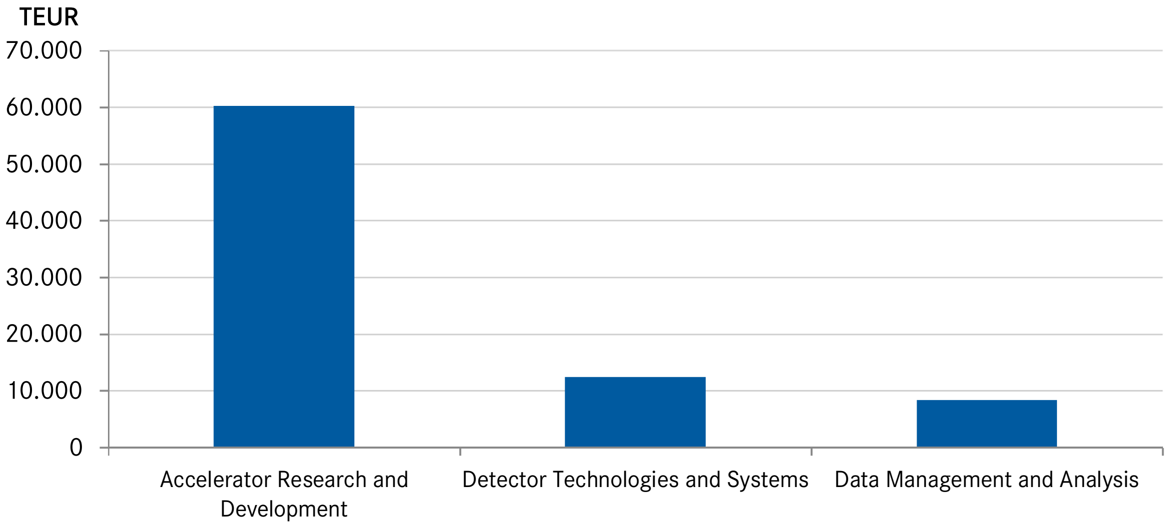


Figure 1: Program costs in 2021 by Topics. For details see Table 8.

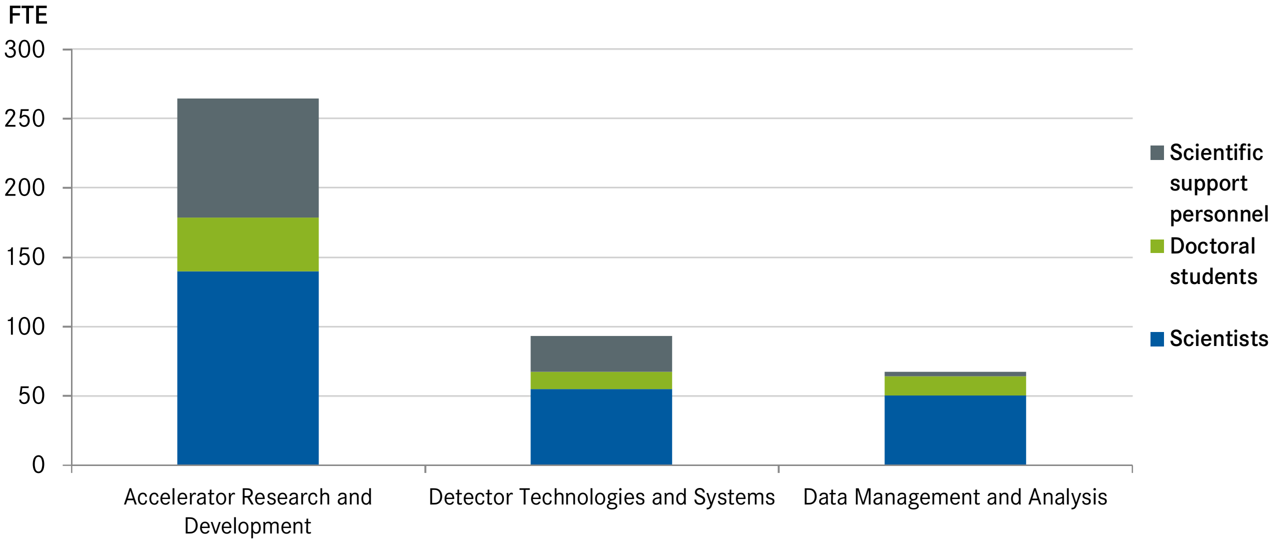


Figure 2: Foreseen personnel resource distribution for activities in the Program in 2021. For details see Table 8.

2. RESEARCH PROGRAM

Technologies are central to the work we do in the Research Field *Matter.* Accelerators, detectors, and scientific computing are key ingredients for successful research. The next decade promises to be a period of time where we can expect great advances, even breakthroughs, in these enabling technologies. Our research program, which we outline on the next pages, has been designed to optimize the potential for breakthrough developments, while at the same time providing a solid and realistic roadmap for advancing technologies needed in *Matter.* Typical for *Matter* in general and MT in particular is a close interrelationship between the research objectives and the technological limitations, one pushing the other to ever more ambitious projects.

In all three Topics in MT, our ambition is to be in an internationally leading position, so that we can optimally contribute to the scientific roadmap we in *Matter* and the Helmholtz Association have defined. We thus contribute to the overall Helmholtz mission by enabling outstanding science in all areas of *Matter* while doing excellent science on technologies within the Program MT.

2.1. Objectives and Strategy

The big scientific questions addressed in *Matter* constantly challenge the limits of the underlying technologies. New technological developments, on the other hand, open directions of research that were unthinkable before. Our strategy and our objectives are designed to allow both directions of interactions: They build on the remarkable results from PoF III, but extend them significantly both in scope and in ambition, while remaining open and adaptable for unexpected new developments. As a Program that develops enabling technologies to address the big scientific questions in the Research Field *Matter*, we naturally play a central role in the definition of roadmaps and strategies that go well beyond our national framework, thus providing essential input to the political decision makers.

2.1.1. Challenges

The development of novel, e.g. plasma wakefield-based accelerators is simultaneously a key challenge and a central goal. Breakthrough results in this area might transform the way we do research in *Matter*. The tremendous progress in novel accelerator technologies seen over the last years allows us to formulate as our key challenge that we make the transition towards the realization of a user facility based on novel accelerator technologies. In parallel to these developments, RF-based accelerators have experienced exciting and great progress. The further advancement of efficient and reliable superconducting (SC) continuous-wave (CW) accelerator technology with all the required components will be one of our central challenges in this area. More generally, we need to satisfy demands from very different systems like electron, hadron and ion accelerators. They challenge the current technological limits in all relevant dimensions. At the same time, we require that these systems deliver highest stability and flexibility for efficient user operation, which adds to the challenge.

Sophisticated detectors are needed in all areas of *Matter* research and present challenges at multiple levels. Modern experiments require detectors that are sensitive over an extremely broad energy range, from sub-eV to PeV, can cover large areas, and have high spatial and timing resolution. This is becoming even more demanding because we increasingly need to combine functions that have so far only been available in separate systems. The breadth of technologies and the wide range of experiments we are required to support present a great opportunity and enable us to exploit numerous synergies. Particular complexities exist for both, the large-scale installations at e.g. the

European XFEL, HL-LHC, or FAIR, as well as for the high-repetition rate high-resolution instruments for accelerator diagnostics.

Scientific computing is more and more becoming the central hinge-pin needed to get optimal results in *Matter*. We have to recognize scientific computing as a research area of its own, not only seen as a service provider, but as a centrally important scientific discipline for *Matter.* The infrastructure required for this research will need to comprise hardware, software, and data. Setting up this infrastructure for *Matter*, developing and making available novel and advanced tools, and participating in the development of new methods at the edge of what is possible is our central challenge in this area.

2.1.2. Research Environment

The Program MT operates and is defined on the basis of the strong and powerful research centers that participate in the Program. We combine fundamental research into novel technologies with focused research for specific applications and the construction of real-life systems. To this end, we foster an environment that creates the freedom to try new things and to perform R&D that could be potentially game-changing. At the same time, we are strongly focused on building systems, integrating them, and eventually making them work.

A central part of our research environment is a strong infrastructure. Locally at the MT centers, excellent environments for research into accelerators and detectors have been developed. Decisive advances were the coordinated moves of several centers towards common infrastructures – most prominently the buildup of the distributed ATHENA infrastructure to enable cutting edge research into laser-driven plasma acceleration. We hope to see a similar effect when the Helmholtz Distributed Detector Laboratory (DDL), for which we have submitted a proposal in July 2019, will be realized within the PoF IV period. Hardware, software, and data infrastructure for the digitalization of the scientific process within *Matter* will be set up in a distributed and federated way, i.e. at the Helmholtz centers, with a central entry point to this infrastructure. This will ensure that we have at our disposal the needed infrastructure for accelerator research, detector research, and scientific computing within the Research Field *Matter*.

The research done in the Program MT is characterized by strong cooperation among the different centers and Topics as well as many and strong international partnerships with numerous other centers around the world. This networking and cooperative structure is essential to ensure that we can work with a very broad range of scientific disciplines and thus fulfill our role of enabling the research of tomorrow. Scientists from MT hold central positions in many national, European, and international projects, for example LEAPS, AIDA2020, EuPRAXIA, EOSC, and many others.

Most of our scientists have a double role – they are engaged in cutting-edge research in MT and at the same time play important roles in one or several of the other *Matter* Programs. This close relation between people in MT, MU, and MML ensures that we are constantly driven by the demands of science, and that we constantly adjust our goals and issues to the most demanding and difficult challenges in MU and MML. Close interactions exist as well with related Research Fields, i.e. *Information* and *Energy*, in particular within the Cross-Cutting Activities (see Volume I, Chapter 5).

In general people are our main asset, and we profit enormously from a vibrant and large community of highly motivated innovative scientists, who drive our research and carry know-how into other fields of science and society.

The combination of several centers, excellent people and a well-developed and broad infrastructure produces an environment which is unique world-wide.

2.1.3. Objectives

We have identified a number of key objectives that we intend to meet over the coming decade. Central to our whole work is our aim to continue to work on the development of a broad technological portfolio geared towards the needs and challenges of the Research Field *Matter*. We are convinced that, with the creation of the Program MT at the beginning of PoF III, we have put down the right foundation to achieve this goal.

Our Research Field relies on accelerators for most of the research we do. One of our central objectives will be to advance novel plasma based concepts to the point where we can design and build a facility based on these technologies. A key part of this will be the startup of the distributed ATHENA facility and the laying of the foundation for the realisation of a user facility based on these technologies. With the promise of a much more compact facility, we believe that we can significantly advance the capabilities of our Research Field. We realize that there are still significant risks, and great advances are needed to meet this objective. Still at the heart of our research is the advancement of RF-based accelerators, and we continue to further the development of superconducting and normal-conducting technologies, in particular continuous wave (CW) superconducting radio frequency (SRF). Diagnostics will play a central role in these efforts, and developing advanced diagnostic tools and improving our understanding of beam dynamics for the whole breadth of application remains a central objective for us.

Progress in our field is intimately connected with equivalent progress in detectors and scientific computing, and is particular closely related to advances in accelerator technologies. With the creation of the Topic MT-DTS in PoF III, we have started a process to fully align and coordinate the efforts in detector development across *Matter*. In PoF IV, our main structural objective will be to extend this cooperation significantly further towards shared infrastructures. Thus, we propose to found the Helmholtz Distributed Detector Laboratory, DDL. Once established, DDL is expected to become an international hub for detector technologies. Our main objective continues to be the development of advanced detector technologies and systems accessible to researchers in *Matter*. A number of paradigm changing technologies will be evaluated for future experiments, in particular in the area of semiconductor detectors. We will explore cryogenic sensors of ultimate energy resolution for a rich spectrum of applications. Major advances in data transfer and real-time processing of highest detector rates will be realized.

In PoF IV, the new Topic *Data Management and Analysis* (MT-DMA) will be established to bring together the expertise in scientific computing and large-scale data analysis within *Matter*. We want to establish MT-DMA as a new Topic within *Matter* with equal success to MT-ARD and MT-DTS in PoF III. To this end, a particular aim will be to increase the level of cooperation across the participating centers as well as between experts in scientific computing, data analysis, and researchers from the scientific domains represented in *Matter*. A key objective will then be to make common tools and methods available to all the communities in *Matter* in a highly transparent manner.

We are convinced that, with the creation of the Program MT in 2015, we have built a strong foundation for meeting the upcoming challenges.

2.1.4. Strategy

MT is a Program with a strong technological aspect and a strong commitment to develop technologies that serve science. It is however also a Program that has been designed for and gets its justification from doing high-risk cutting edge research, in order to encourage new and potentially game-changing technologies and applications. The success of MT depends on this dual approach, which is at the core of our strategy.

The development of powerful and cost-effective accelerators is a key priority for us. Recent developments in novel accelerator technologies, driven by results from MT, allow us to push strongly towards implementing these technologies in a real facility. We further this at several levels – at the center, national, and European level. The backbone of accelerators, however, remains RF-based accelerators, also in PoF IV. Optimized and tailored RF systems will drive such accelerators forward. We continue to promote the development of both superconducting and normal-conducting technologies for the advancement of the existing and future accelerator-based large-scale research facilities of the Helmholtz Association, but also for other key infrastructures, e.g. at the high-energy frontier, such as FCC or CLIC. Here, the efficient and synergetic use of our test facilities and infrastructure plays a central role. The two international user facilities European XFEL and FAIR rely on these developments, and together with the suite of upgrades of our photon facilities dominate our work program.

We have identified promising sensor, microchip and data processing technologies which offer the prospect of realizing extremely powerful detector systems for the exploitation of experiments at the European XFEL, future light sources or particle colliders. We enable the understanding of novel acceleration concepts by advanced and ultrafast beam diagnostics. In order to promote astroparticle physics experiments, for example dark matter searches and neutrino physics, we are developing sensors of ultimate resolution. A key part of our strategy is a coherent effort across all centers to develop our infrastructure and coordinate the needed tools and capacities more closely. The realization of the Helmholtz Distributed Detector Laboratory (DDL) as strongly requested in the scientific evaluation will be a central element to implement this strategy.

We are focusing our strategic efforts to remove the obstacles limiting the scientific harvest from accelerators and experiments on three important levels of data processing. We will create the hardware and software infrastructures needed to deal with the huge amounts of data produced at unprecedented rates at all facilities. We will develop and apply cutting edge technologies from Exascale-ready computing to machine learning for knowledge-informed online data reduction. Finally, we will enable a fast and early feedback to the facilities, based on data taken or simulations performed. These will greatly enhance experimental conditions during the critical phase when experiments are running at the facilities. Together with the strong central data storage and processing facility IDAF, this topic will be a central part of our strategy for the next years. As part of this strategy, some realignment has taken place, with efforts moving from either MT-ARD or MT-DTS to MT-DMA to reflect the increasing importance we assign to scientific computing.

Overall our strategy rests on a collaborative approach to the defined objectives, in order to maximize synergies and build on the individual competences of the participating centers. Continuous readjustment of our targets is part of the nature of our Program and is reflected in the milestones defined in the Topics. This ensures that we stay tuned to the requirements of the user communities and allows us to include breakthrough results. Regular meetings are organized to obtain consensus on any change of direction, decide necessary adaptation of the strategy including the identification of new objectives, and further the promotion of education and training (see Chapter 3.3.).

2.1.5. Outlook

Building on our success in establishing the Helmholtz Association internationally as a key player in the development of novel and advanced accelerator and detector technologies, we have proposed a plan to carry this effort into the future. We are convinced that by combining forces across the entire Research Field *Matter* in this area of central importance, we can significantly enhance our contribution in solving grand challenges in the Helmholtz Association. The role of technologies for the success of our scientific mission is becoming more pivotal than ever, and breakthrough developments such as plasma-based acceleration might completely transform our field and our work. For this reason, we have set up the Program MT, so that we are well positioned to face the challenges of the next decade, and have defined a roadmap that will lead us well beyond the PoF IV funding period.

2.2. Structure of the Program

Accelerators, detectors, and data define the three Topics of the Program MT: *Accelerator Research and Development* (MT-ARD), *Detector Technologies and Systems* (MT-DTS), and *Data Management and Analysis* (MT-DMA). The structure of the Program including the contributing centers is depicted in Figure 3.

In MT-ARD, we extend the limits of conventional accelerators and concepts for new accelerators and develop their applications. In MT-DTS, we optimize sensors, develop new detection methods, and build prototype systems to face the challenges of current and future experiments. MT-DMA will develop methods for successfully handling, processing, and analyzing the large amounts of data of unprecedented complexity at high rates stemming from experiments within the Research Field *Matter*, thus enabling the analysis of more and more complex systems.

Each of the Topics is structured in four (MT-ARD) or three (MT-DTS, MT-DMA) Subtopics to further focus the research and strengthen the fruitful cooperation between the participating Helmholtz centers and institutes. Beyond the Helmholtz centers, the cooperation with universities and other national and international research organizations is of key importance for the Program.

With the Interdisciplinary Data and Analysis Facility (IDAF), there will be a LK II facility associated to the Program in PoF IV. The IDAF, located at DESY in Hamburg, will serve the *Matter* community as a data center with expanded scope compared to PoF III (where the predecessor Tier-2 was associated to the Program MU). Keeping the obligations to the LHC experiments, the IDAF will in addition be extensively used for the scientific analysis of research with photons, accelerator research, and astroparticle physics, and for compute-intense applications from all three Topics.

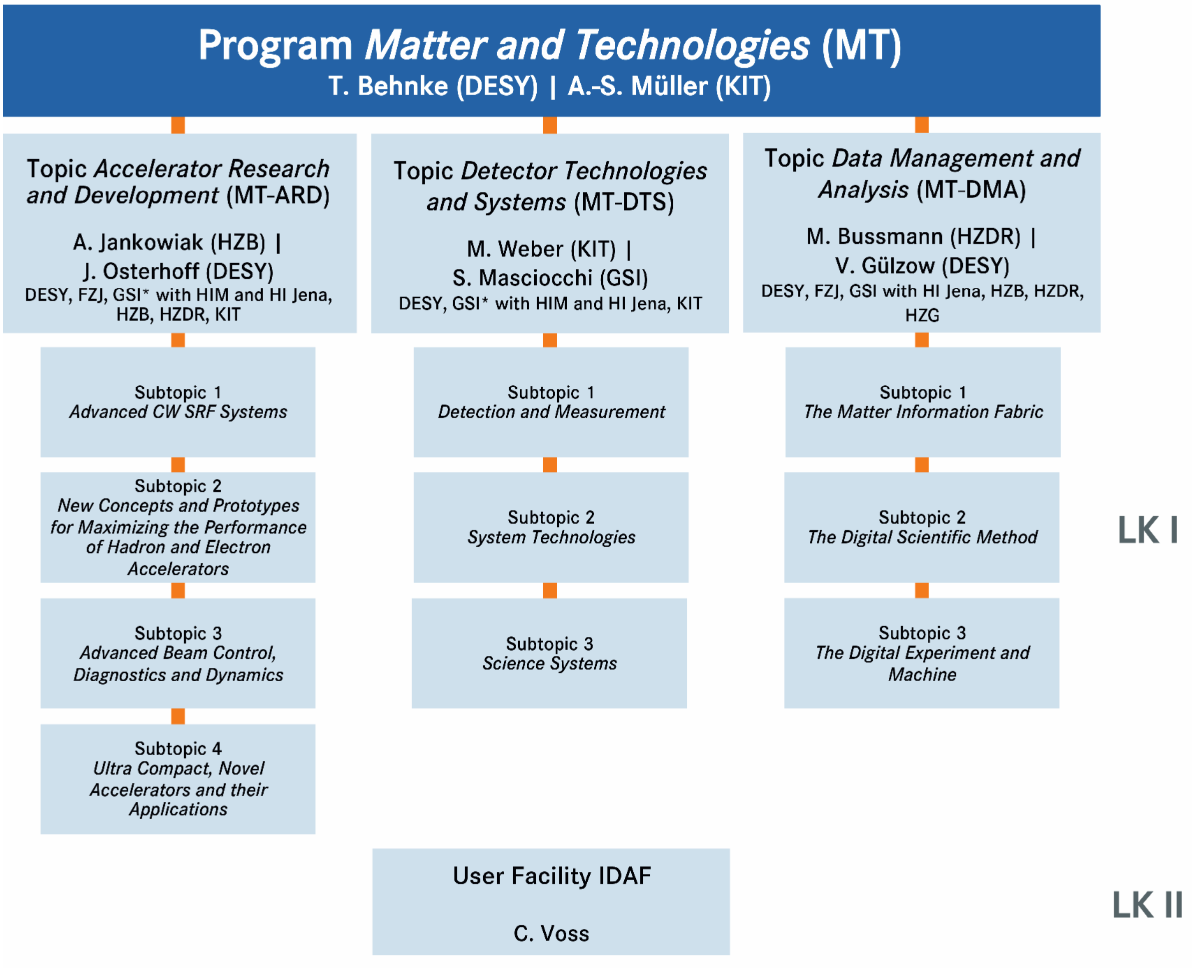


Figure 3: Structure of the Program MT with its three Topics MT-ARD, MT-DTS, and MT-DMA as well as their Subtopics and the associated LK II infrastructure IDAF.

** GSI and FZJ contribute to this Topic also through TransFAIR. TransFAIR denotes the activities of the FZJ Institut für Kernphysik (IKP), which are planned to be transferred to GSI during PoF IV.*

2.2.1. Topic Accelerator Research and Development

Executive Summary

Within MT-ARD, six Helmholtz centers and two Helmholtz institutes, together with their national and international partners, collaborate closely to advance the state of the art in accelerator science and technologies. The activities of MT-ARD contribute substantially to the future expansion of capabilities of large-scale accelerator-based research facilities within the Helmholtz Association and beyond and, at the same time, serve to develop novel disruptive concepts and methods. As such, these endeavors form the foundation and nucleus for the continued scientific leadership of the Research Field *Matter* in decoding the structure and function of matter, materials, and biological systems. As MT-ARD is a true cross-disciplinary endeavor linking science and technology, it offers an ideal environment to integrate M.Sc., Ph.D., postdoc researchers, and early career technicians and engineers.

Strategy

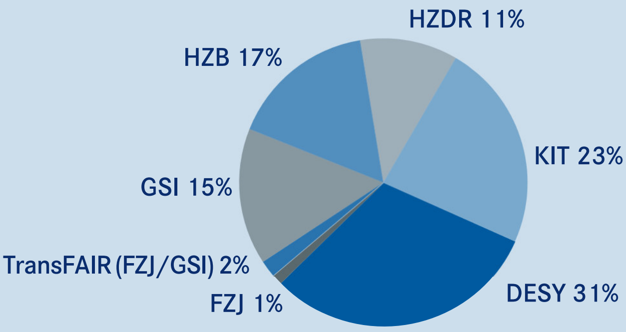
Our strategy is a consequent evolution of the successful approach established with PoF III. The focused research and development program is organized in four Subtopics, reflecting the four major research goals: Advanced CW SRF Systems (ST1); New Concepts and Prototypes for Maximizing the Performance of Hadron and Electron Accelerators (ST2); Advanced Beam Control, Diagnostics and Dynamics (ST3); and Ultra Compact, Novel Accelerators and their Applications (ST4). The research activities take place in an interlinked scientific network guided by an established cross-institutional management structure. The scientists of the four Subtopics closely interact not only within MT-ARD, but also with the Topics MT-DTS and MT-DMA. Our work is synchronized with the other Programs of *Matter*, and active links exist to other Helmholtz Research Fields such as *Health* and *Energy*. Beyond this lively network, the intense exploitation of dedicated test facilities and setups within MT-ARD is essential for rapid scientific advances. These test facilities also act as catalysts and hubs for our technology transfer activities.

Facts and Figures

Participating centers:
DESY, FZJ, GSI with HI Jena and HIM, HZB, HZDR, KIT, FZJ and GSI through TransFAIR[1]

Spokespersons:
Andreas Jankowiak (HZB),
Jens Osterhoff (DESY)

Core-funded scientists: 139 FTE (2021)
Core-financed costs: 60,2 MEUR (2021)



Contributions of the centers to Topic MT-ARD:
Total core-funded FTE in 2021

Strategic Goal of the Topic

MT-ARD is advancing fundamental and applied science and forefront technologies for the improvement of state-of-the-art accelerator concepts and the emergence of novel disruptive methods and paradigms. In the upcoming funding period, we will work on developing ultra-compact, cost-efficient, high-gradient plasma-based accelerators as an alternative to the current, large accelerators for applications in science, industry, and medicine. Compact accelerator technology may lead to a paradigm shift in this respect. It will allow us to bring the accelerator to the problem to be studied – not the other way around – with far-reaching societal implications. The basis for these developments has been strongly supported by the decision of the Helmholtz Association in PoF III to fund the ATHENA infrastructure, whose results will be leveraged to its full extent.

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[1] *TransFAIR denotes the activities of the FZJ Institut für Kernphysik (IKP), which are planned to be transferred to GSI during PoF IV.*

In addition to these high-risk, high-reward goals, we will build on our unique infrastructures and know-how to evolve technologies and methods for upgrading existing or planned accelerator facilities. The development of reliable, efficient CW operation of SRF accelerators for immediate integration into linear accelerators for electrons and hadrons and into storage rings is of high priority. A significant impact is expected for applications at the European XFEL, DALI, and BESSY VSR, as well as for the synthesis of super-heavy elements at GSI. The optimization of beam parameters for achieving ultimate intensities, stability, and flexibility constitutes another anchor point of the MT-ARD strategy. Such research will be critical to maximize the impact of upcoming synchrotron light sources such as diffraction-limited storage rings (e.g. PETRA IV, BESSY III) and next-generation hadron accelerators (e.g. FAIR). All of these developments are accompanied by progress and innovation towards high-fidelity beam controls and dynamics. These are facilitated by the expected advancements in femtosecond and attosecond timing and diagnostics, leading to next-generation feedback systems, which are to be realized in close cooperation with experts from the Topics MT-DTS and MT-DMA.

The MT-ARD Subtopic structure and our work program take into account the recommendations of the scientific evaluation. With the activities in the field of plasma acceleration of electrons and hadrons, in particular the establishment of the ATHENA project, with regard to applications; we will meet the requirements of a rapid development of this transformative technology. The available test infrastructures, which are pivotal for the execution of our research program, will be further expanded (e.g. SupraLab, SINBAD, cSTART) and consolidated (e.g. ATP accelerators, SHE Demonstrator). Our work program will contribute significantly to the further development of the existing and future large-scale facilities of the Helmholtz Association. Technological solutions for future accelerators at the high energy frontier (e.g., FCC, CLIC), developed in close cooperation with CERN, will help to address the challenges that lie ahead of us as we devise the next experimental tools for particle physics. Also here, the collaboration of scientists from many technology-affine disciplines, which is characteristic of MT in general, is a forte.

Competences

MT-ARD approaches the scientific and technical challenges in PoF IV under outstanding starting conditions. The involved centers and partners have established a position or consolidated themselves among the world leaders in their respective domain, as corroborated by the final report of the scientific evaluation of the Helmholtz centers contributing to MT-ARD in PoF III.

Our leadership role in CW SCRF cavity technology is evident. Several new flagship-level projects worldwide (e.g. LCLS-II) employ sophisticated designs developed by Helmholtz partners over the past decades. Vital for this success is the cross-center research facilitated by MT-ARD, which heavily relies on the complementary expertise in each of the centers. This applies equally to the available impressive infrastructures – from sample development and cavity testing [1][2][3] through SRF photoinjector test stands [5] to full module characterization [4].

We have built and we operate high-intensity heavy-ion beam facilities that provide world-leading intensities. We can rely on a broad range of competences and leading experts in this field, as proven by the efficient and flexible operation of our facilities, which provide e.g. up to three different ion species from cycle to cycle. The ongoing development toward intelligent operator support [6] will further enhance the efficiency. We have developed unique technologies to overcome limitations by charge exchange processes in a strongly dynamic vacuum background to reach the space charge limit for all ions species [7], and a broad variety of beam cooling techniques [8] to approach ultimate beam qualities, especially for secondary rare-isotope and future antiproton beams. Cutting-edge technologies, developed at the participating centers, also in cross-topic and cross-research-field activities, are an asset to the research program of MT-ARD. As a key technology for FAIR, various types of fast-ramped superconducting magnets have been successfully built [9], including a tested fast-ramping 4.5 T model dipole.

Additional examples are the worldwide acknowledged development of a superconducting low-loss Rutherford cable and energy system studies with unique infrastructures such as the Energy Lab 2.0 [10].

In addition, we are working on the development of concepts for new operation modes, e.g. for synchrotron light sources. A promising scheme allows the simultaneous storage of arbitrary fill patterns on multiple orbits, combining timing capabilities with simultaneous high-brilliance operation [11]. The implementation of this concept as a future standard operation mode is on the horizon.

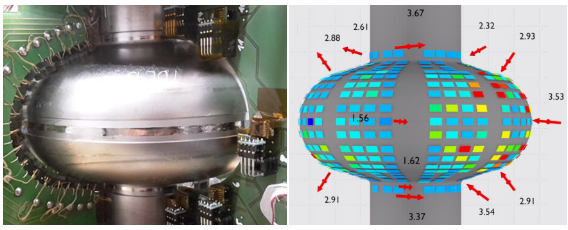


Figure 4: New 3D magnetic-flux mapping enables the study of RF power dissipation due to trapped magnetic flux in superconducting cavities (from ARD-ST1).

Based on technology developed in MT-ARD for linear and circular accelerators, ultrashort electron bunches are now available on a regular basis, free-electron lasers have established record parameters in terms of stability and flux [12], and novel acceleration techniques are approaching technological readiness for applications. MT-ARD has established itself as world-leading for the development of cutting-edge diagnostic systems [13] and synchronization technologies [14] – progress that is greatly expedited by standardization and synergies, both within Helmholtz and outside e.g. with industrial partners. With our competences and test facilities, we cover the whole process chain, from modeling [15] through the most advanced measurement systems [16] and precision control [17] to the analysis of large data sets using advanced concepts such as machine learning. In these fields, MT-ARD has made great strides and is today globally recognized as a driver of innovation, a position that will be further strengthened in collaboration with MT-DTS and MT-DMA.

The rapidly growing fields of plasma-based acceleration of electrons and ions [18][19] have experienced tremendous development during the present PoF period, with major contributions from MT-ARD. Their potential is recognized for the next generation of compact particle accelerators with mid- to long-term applications of high societal relevance. Laser wakefield schemes, which are the most advanced and directly applicable, provide inherently ultrashort and synchronized electron bunches ranging from some 10 MeV to near 10 GeV in a single compact stage. Recent progress in injection control and femtoscale diagnostics [20] confirms record peak currents exceeding some 10 kA. MT-ARD is uniquely providing next-generation beam-driven plasma wakefield acceleration [21][22] for high-repetition-rate operation. Furthermore, refined targetry [23] will be a key to enabling proton energies and pulse rates relevant for applications. This research benefits from a world-leading suite of high-power lasers and electron beam drivers provided and advanced by the partners in MT-ARD.

Objectives and Approach

ST1 – Advanced CW SRF Systems: The MT-ARD ST1 goal is to develop SRF science and technology in order to significantly improve the performance of accelerator-based facilities. BESSY VSR, DALI, and the European XFEL all aim for CW operation. CW SRF offers multifaceted advantages: from increased brilliance through greater stability to greater flexibility in pulse patterns and bunch properties, which can thus be tailored to more effectively meet user requirements.

ST1 comprises three key research foci for maximum impact on future SRF infrastructures: **CW SRF injectors** for high-brightness electron beam generation, **CW SRF technologies** of electrons and hadrons, and development of new **CW SRF materials** to outperform state-of-the-art niobium. These activities also provide the foundation for **industry partnerships** to develop robust, cost-effective turn-key SRF units and design compact SRF accelerators for various applications.

The cross-center approach encouraged by MT-ARD pools complementary expertise in the participating centers. ST1 activities also benefit greatly from international collaborations. Most active is the TESLA Technology Collaboration, in which the Helmholtz partners play a major role. Many fundamental developments in ST1 profit from work done in the context of large-scale Helmholtz projects, as e.g. the European XFEL.

Building on the Helmholtz Gun Cluster collaboration, **CW SRF injectors** targets high-brilliance CW electron sources for various applications. While HZDR is developing injectors for high-field THz generation, HZB is studying high-current sources for facilities such as ERLs. DESY's focus is on an all-superconducting source matched to the needs of CW free-electron lasers (FELs). The existing and future injector test facilities are complementary, while their different foci are most visibly expressed by the choices of cathode material. The complexity of SRF injectors calls for a multicenter development campaign for technical systems such as cryostats, solenoids, and cathode handling. Compatible designs ensure that test stands are adapted to each center's need. The feasibility of SRF injectors will be demonstrated by 2025 [ARD-4].

CW SRF technologies targets generic systems that address CW operation of future facilities: CW FELs (FLASH/European XFEL), high-current storage rings (BESSY VSR), coherent THz sources (DALI), and high-current heavy-ion beam sources (SHE production). Though each facility is different, much underlying science and technology bear commonality. Some examples that benefit heavily from knowledge transfer are construction materials and technical solutions for cryogenics, couplers, tuners, and piezo actuators. The goal is to develop a set of "recipes" for CW-specific aspects of future SRF system operation [ARD-5, ARD-6]. Mixing and matching these concepts then helps to develop tailored SRF designs. An example is the complex surface preparation of the new GSI/HIM Crossbar H-mode cavities for ions, which expands upon methods for $\beta=1$ cavities. Particularly challenging is RF field control: Active feedback and microphonics compensation are essential for ultra-stable, low-RF-power CW operation. The next step will be to consolidate the activities, be it design considerations for cryostats or the development of LLRF and piezo compensation systems as demonstrated in European XFEL module CW tests or in SupraLab's HoBiCaT facility.

Large SRF accelerators require large-scale cryogenic plants for heat-load handling. Compact accelerators for use in small-scale laboratories, on the other hand, should only need low-maintenance, compact cryogenic cooling. CW operation in both cases exacerbates this situation, pushing the cryoplant to the technical and financial limit. **CW SRF materials** specifically address this issue. Recent CW projects employ the new technology of nitrogen doping of niobium, and we are now investigating improved nitrogen infusion. While these semi-established techniques reduce losses, ≤ 2 K operation is still mandatory. Magnetic flux-trapping related losses too remain an impediment to large-scale CW applications. For these studies, we are developing novel diagnostics and sample testing based on quadrupole resonators. Ultimately, we will investigate materials such as Nb_3Sn and multilayer SC-insulator-SC systems to evaluate their potential for ≥ 4 K operation [ARD-3]. If successful, these activities will pave the way for cryo-cooler-based cryogenics for compact industry and university accelerators.

ST2 – New Concepts and Prototypes for Maximizing the Performance of Hadron and Electron Accelerators: MT-ARD ST2 aims for leadership in strategic technologies for hadron and electron accelerators. It involves new concepts for increased beam intensities, the generation and conservation of high-quality beams, and performance upgrades of existing user facilities. The knowledge gained by ST2 will assure a central and visible role of the Helmholtz accelerator laboratories in upcoming international large-scale projects. Concepts for exceeding the presently known limitations for intensity and quality will be investigated. The operation of existing user facilities will benefit from integrated accelerator control systems, which provide the foundation for advanced operator support.

Beam intensity frontier: For the generation of pulsed and CW high-intensity heavy-ion beams, we will investigate high-repetition-rate heavy-ion plasma sources and CW, low-beta front-ends, e.g. for superconducting CW linear accelerators as addressed in ST1. New stripping technologies, e.g. high-pressure gas jets, plasma strippers, or strippers for multiple charge states, will lead to higher stripping efficiencies for heavy ions. To further increase the intensity of beams in driver or injector synchrotrons to values above their presently achieved limits, we will tackle the main intensity limitation – the incoherent space charge limit – in two ways: a) by operation with low-charge-state heavy ions and b) by compensation of the transverse space charge detuning by electron lenses [ARD-8].

Beam quality frontier: A major goal within this area is the development and installation of the world's first laser cooling facility as part of a user synchrotron. Laser cooling will not only provide better beam quality, but will also be used to generate extremely short heavy-ion bunches. We will apply the technology of electron coolers to beams with energies much higher than previously achieved. Significantly greater technical effort will be necessary to generate electron beams with the required high energy and quality. The technical design will be accompanied by advanced models for the cooling of hadron beams. More efficient designs of stochastic cooling systems (e.g. slot ring couplers) promise beam cooling in all six phase space dimensions and may even be applied to counter-rotating beams in a common beam pipe. A new quality for electron beams in storage rings, targeting the longitudinal phase space, will be studied with the step-wise implementation of the BESSY VSR mode. This is a new operation regime, that uses multi-frequency, multi-cell CW SC cavities to generate high-current picosecond or low-current sub-picosecond bunches in a beating mode. If successful this would allow the simultaneous storage of alternating short (picosecond) and long (some 10 picosecond) electron bunches. With the commissioning of bERLinPro, new standards for the intensity and quality of CW electron accelerators will be set.

Figure 5: R&D model of a superconducting dipole magnet for ramp rates of 1 T/s (from ARD-ST2).

Beam precision frontier: Our foremost goal is to significantly improve the performance and efficiency of operation of existing user facilities in terms of setting and controls of the machines. By means of automated and intelligent operator support systems, and in a joint effort with MT-ARD ST3 and MT-DMA ST3, we will enhance the quality and reproducibility of quality of the generated ion and electron beams, as well as the usable beam time. The level of precision of beam control so far only reached in electron machines will be adapted to hadron synchrotrons and storage rings. Corresponding integrated automatic orbit control, tune and chromaticity correction, and feedback systems will be developed and implemented [ARD-9]. We will also explore new operation schemes, such as the generation of transverse resonance island buckets (TRIBs) in BESSY II. The goal is to bring previously developed concepts to user operation readiness. Generic studies using multiband achromat (MBA) lattices for a conceptual design of future low-emittance electron storage ring light sources with integrated timing capabilities, which provide time resolution together with high-brilliance and high-coherence operation, will complement the research program.

Technology frontier: For future accelerator projects, it is crucial to maintain our world-class know-how in superconducting magnet technologies in the Helmholtz centers and to accompany major worldwide trends in this field. The high-field superconducting magnet frontiers, with relevance for example for the FCC study, and the goal to demonstrate the feasibility of 16 T dipole fields will be addressed. The worldwide unique and successful developments towards fast-ramped superconducting magnets, with ramp rates far above the values achieved so far, will be continued [ARD-7]. These activities are accompanied by the development of superconducting undulators for future diffraction-limited light sources as well as for use in free-electron lasers. ST2 will also aim for solutions to major technical issues, with a high performance impact, for new large-scale high-energy accelerator projects such as FCC or compact, scalable accelerator-based neutron sources (HBS).

ST3 – Advanced Beam Control, Diagnostics and Dynamics: With increasing demands on beam parameters, stability, reliability, and reproducibility, the requirement of controlling the beams delivered to experiments has become paramount.. Here, the term “control” extends beyond RF controls and control systems to include complex high-resolution, high-repetition-rate sensor networks based on a deep understanding of the complex beam dynamics. Accordingly, our strategy for MT-ARD ST3 focuses on developments of instruments and methods, both experimental and theoretical, to tackle a large dynamical range in all relevant parameters. Advanced feedback systems will be employed to achieve unprecedented stabilization. **Attosecond metrology** will be crucial to achieve the next level of time resolution in accelerator-based experiments. While the scope of the research program aims at the synergetic use of technologies and methods for all types of next-generation beams, the generation, detection, and control of those ultrashort electron bunches remains at the core of our activities. Combining advanced methods of machine learning and data analysis with state-of-the-art theory/simulation and precision control and metrology in extended sensor networks, a new level in understanding system integration can be accomplished. This might enable breakthrough achievements in areas far beyond accelerator technology and can have impact on industrial and societal applications.

The new methods and techniques approached by ST3 require an iterative development and benchmarking experiments from the demonstration stage to the final hands-off implementation at user facilities. Exploring the **dynamics of custom beams** at the forefront of today’s technology is a prerequisite for the design of future high-performance or compact accelerators. Customized beams cover a large dynamical range in terms of both pulse length and bunch charge or beam energy – a challenge for presently available simulation codes. To achieve a reliable

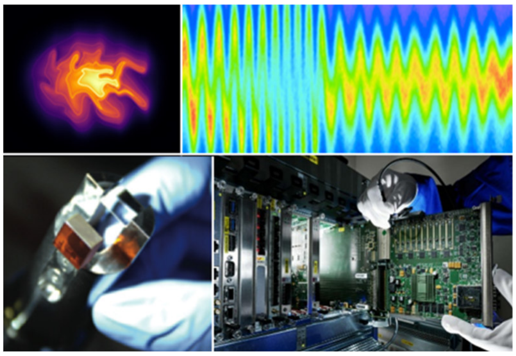


Figure 6: Advanced diagnostics and control of complex beam dynamics (from ARD-ST3).

generation of attosecond to femtosecond electron pulses in free-electron lasers, we will establish improved start-to-end modeling, in close collaboration with MT-DMA ST3, considering all relevant aspects from the electron source dynamics to the mitigation of harmful collective effects, e.g. in bunch compressors [ARD-12]. Generating high-repetition-rate coherent radiation from exploratory operation modes (e.g. multiple-orbit schemes, modulated phase space) with picosecond bunches in storage ring light sources and reaching the highest electromagnetic fields are further topics addressed in our work program [ARD-10]. New and extended simulation tools will be the basis for achieving the highest possible ion beam currents and the demonstration of low-energy transport of these beams, profiting from the wide range of expertise in the participating centers. Progress in high-throughput beam diagnostics and accelerator modeling enables the envisaged systematic studies of transient phenomena, of the physics of instabilities and, in general, of the beam dynamics in the non-equilibrium case.

To address the aforementioned challenges, **extreme-range beam diagnostics** for exploring all relevant parameters for tomorrow's beams in the time and frequency domain and for application to particle (electrons, protons, ions) and photon beams need to be studied in ST3. Diagnostics are the crucial link between beam dynamics and control. With the PolariX transverse deflector, for example, femtosecond beams can now be resolved in all dimensions. New techniques such as laser-driven THz pulse streaking and spectrometers resolving coherent radiation will allow for unprecedented, in-depth longitudinal phase space analysis.

Implementing the detection of large dynamic ranges or extreme values of beam positions, bunch charges (from very low to extremely high intensities) or arrival times is a common challenge across the participating centers and will be addressed in close collaboration. For non-destructive measurements of high-repetition-rate beams, fast 1D (e.g. KALYPSO) and 2D detectors will become increasingly relevant to determine intra-bunch parameters in a single shot, and by providing low-latency outputs. These detectors will be key components in advanced feedbacks loops for stabilization. In this area a close collaboration with MT-DTS exists and is central to the success of this task.

Accelerator **stability, control, and synchronization** using state-of-the-art technologies, such as high-speed digital electronics, low-noise detector systems, and novel feedback algorithms implemented in powerful field programmable gate arrays (FPGAs) acting on multiple manipulators simultaneously, are key ingredient to ensure the stability of next-generation accelerators [ARD-11]. For advanced feedback control, for example, we will use real-time beam dynamics simulation, which enable improved control over the accelerator. Beyond femtosecond-stable reference systems, developed during PoF III, synchronization control also requires the preservation of the synchronization stability in the downstream subsystems, such as high-power lasers or RF power sources. RF control requires new RF phase detectors with attosecond field resolution to meet future goals. Of increased importance is laser control of particle beams, e.g. using advanced laser pulse shaping techniques adapted via precision online diagnostics as well as techniques to minimize the beam emittance, tailor electron beams for THz emission, or synthesize XUV photon pulses through external seeding.

ST4 – Ultra Compact, Novel Accelerators and their Applications: The strategy of MT-ARD ST4 is to focus the world-leading activities of the Helmholtz partners in advanced plasma and RF accelerator research on the development of compact accelerators up to application readiness, in particular by exploiting the research infrastructure ATHENA [ARD-13] and leveraging European design studies (EuPRAXIA). Improved beam control is key to this strategy and relies on a fundamental understanding of the acceleration processes, gained through innovative metrology developed in the INF project on femtoscale probing and linked to ST3. Predictive simulation capabilities, which benefit from the new Topic MT-DMA, further link microscopic and macroscopic acceleration parameters. As a high throughput capability is critical to application readiness, high-average-power drive beam (ST1) and laser development gains importance. The Research Field *Matter* and the cooperation with internationally leading German industrial companies provide ideal starting conditions for these developments.

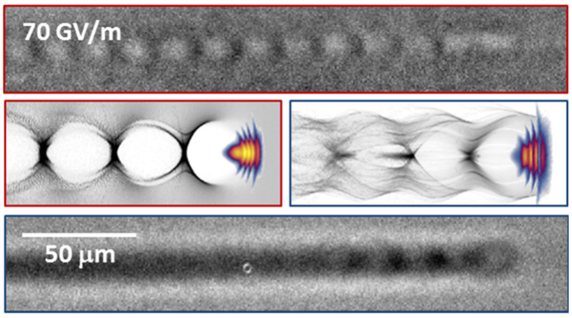


Figure 7: Simulation and visualization of plasma wakefields on the femtoscale (from ARD-ST4).

Plasma wakefield acceleration of electrons: We strive to improve beam parameters such as charge, bandwidth, and emittance from laser-driven wakefield acceleration (LWFA) in order to create bright secondary radiation sources ranging from high-field THz through soft X-rays to gamma rays for applications in coherent control of matter, high-field QED, medical imaging, and warm dense matter probing. Our ultimate goal of demonstrating free-electron laser gain with compact technology requires unprecedented phase space manipulation capability of bunch slice properties as well as dedicated undulator development [ARD-15]. Approaches on external injection and combining advanced RF technology with plasma accelerators as compact injectors for multistage accelerators and storage rings, for phase space rotation and ultimate slice parameter diagnostics are pursued in the framework of ATHENA. Challenges related to beam-driven plasma wakefield acceleration (PWFA), including reduction of energy spread, increase of energy efficiency, and especially high-power operation can be addressed at the unique FLASHForward facility, where intense ultrahigh-quality electron bunches are available from a superconducting high-power linac. Recent progress in LWFA injection control has resulted in record peak currents exceeding some ten kA, making the beams also suitable as compact drive beams for a hybrid LWFA–PWFA scheme and offering the potential to produce high-energy, high-quality beams in a compact footprint. In parallel, concepts relying on dielectric or metallic THz- or laser-field-driven microstructures are being pursued to deeply understand the potential of electron manipulation with electromagnetic waves and structures, as a potential ultracompact source of low-energy electron beams.

Laser ion acceleration is being demonstrated to provide proton energies exceeding 50 MeV for ultrashort-pulse lasers and 100 MeV for high-energy lasers in target normal sheath acceleration (TNSA). We will investigate advanced schemes relying on enhanced volumetric energy transfer in the relativistic transparency regime or ultimately on radiation pressure to increase energy and performance. These schemes are known to be increasingly sensitive to details in laser and target parameters. Innovative on-shot laser and plasma diagnostics are thus being prepared to monitor the interaction in real time and are complemented by fully three-dimensional simulation capabilities. These measures, together with dedicated target developments, should allow us to address promising regimes [ARD-14]. The development of ultrahigh laser contrast for diode-pumped laser technology and high-fidelity metrology is expected to enable stable operation in the latter regimes at the ATHENA facility and push the energy frontier to values supporting application studies in radiation oncology. Dedicated compact pulsed magnet beam transport and phase space manipulation as pioneered with the LIGHT beamline operated at GSI will complete the installation of versatile proton irradiation sites.

High average power and pulse repetition rate of advanced accelerators require a paradigm change from single-pulse-based exploratory research to fully automated routine operation. Such operation regimes are challenging in terms of providing and handling the high average power, but they are on the other hand well suited for the use of advanced feedback algorithms and control systems similar to ones used in conventional instruments (ST3). This opens up possibilities for improvement through innovative methods based on artificial intelligence (MT-DMA). High average power, which is equally defined by driver and target technology [ARD-16], will first be achieved in PWFA with FLASHForward. For LWFAs, laser development towards combined high-average-power and high-peak-power operation will be pursued, leveraging industrial developments for advanced high-power machining lasers. For ion acceleration, where the need for high laser pulse energy has already triggered the development of world-leading energy-efficient diode pumping, debris-free and replenishable targetry becomes crucial. Cryogenic or high-pressure gas targets are starting to show their full potential as sources of clean single-species light-ion beams.

Expected Results

The major activities of MT-ARD defined in the work programs of the four Subtopics are reflected as an appropriate set of milestones in Table 1. Two overarching milestones [ARD-1 and ARD-2] echo the fact that MT-ARD activities in general are strongly interlinked to the future needs of national and international user communities, and that many activities in MT-ARD are expected to strongly benefit from machine-learning methods and strategies developed in MT-DMA.

Table 1: Milestones of the work program for the Topic MT-ARD

Milestone		Subtopic	Year
ARD-1	Review of the usage and impact of machine learning on the MT-ARD research program	ST1-4	2023
ARD-2	Updated evaluation of the user needs for guidance of the research program	ST1-4	2024
ARD-3	Review of SRF CW material performance and realignment of studies	ST1	2024
ARD-4	Demonstration of high-brilliance SRF-based electron sources	ST1	2025
ARD-5	Demonstration of CW SRF high-current heavy-ion beam acceleration	ST1	2025
ARD-6	Compilation of recipes for CW SRF accelerating system design and operation	ST1	2026
ARD-7	Design review of high-field and fast-ramped superconducting magnets with assessment and selection of the most promising concepts	ST2	2024
ARD-8	Assessment of the main intensity limitations of large circular accelerators and options to shift them to higher values	ST2	2024
ARD-9	Summary and evaluation of progress in conservation and generation of reliable operation with high beam quality by means of advanced beam controls and cooling concepts	ST2	2026
ARD-10	First-stage demonstration of experimental and theoretical methods for tailored longitudinal phase space generation	ST3	2024
ARD-11	Establishment of routine femtosecond precision operation at short-pulse accelerator facilities	ST3	2025
ARD-12	Demonstration of experimental and theoretical methods for tailored 6D phase space generation	ST3	2027
ARD-13	First availability of jointly developed infrastructure ATHENA	ST4	2022
ARD-14	Understanding of scaling of proton energies and assessment of applications of societal relevance (e.g. tumor therapy)	ST4	2024
ARD-15	Measurement and control of electron beam parameters suitable for FEL pilot user facility	ST4	2025
ARD-16	Substantial increase in average power of plasma accelerators for high-throughput applications	ST4	2027

Synergies and Collaboration

By design, the Topic MT-ARD drives research in a highly collaborative style, both internally and across Topic boundaries, as well as in close interconnection with other Helmholtz Programs and Research Fields and with other leading national and international partners (see Chapter 3.1). Of special importance is the close collaboration with German universities that are active in the field of accelerator physics and technologies, many of them with strong ties to the work program of MT-ARD. Evidently, the basic scientific results emerging from MT-ARD enable and facilitate the groundwork for the design of future LK II facilities in MML and MU and optimize the exploitation of current machines. Among our Subtopics, there exists a highly active exchange on multiple levels, as the components and techniques developed in different Subtopics and even Topics often critically depend on and benefit from each other. One exemplary case among many is the close collaboration between MT-ARD ST3 and ST4 in the design of novel accelerators, which require cutting-edge time-resolved diagnostics and synchronization systems at the frontier of femtosecond/attosecond technology. This collaboration maintains close ties to the Topics MT-DTS for detector development and MT-DMA for machine optimization, development of digital twins of full accelerator systems, enhancing the capabilities of accelerator simulation codes and real time analysis of beam diagnostics with feedback to the machine, with the joint innovation pool project AMALEA providing a seed for these activities. We will explore the applicability of such advanced compact novel plasma-based sources in the Research Fields *Matter* and *Health* for medical imaging applications and in the Research Fields *Matter* and *Information*. This is greatly reinforced by the joint MT-ARD research infrastructure ATHENA as a collaboration focal point. These and many more activities are embedded in a rich international landscape of collaborations, many of them led by Helmholtz centers, in close connection with leading accelerator institutions worldwide. Examples are the TESLA (ST1), EuPRAXIA (ST4), LEAPS, and ARIES (all MT-ARD) collaborations.

The MT-ARD management is organized in a lean structure. Each Subtopic is headed by two expert spokespersons from different Helmholtz centers with excellent connections to the involved and collaborating scientists from other (Sub-)Topics and fields. The Subtopic spokespersons report to the Topic spokespersons, who are closely linked to the Program management and all Helmholtz center representatives for MT-ARD. Decisions are taken in regular board meetings always consisting of the Topic and Subtopic spokespersons and, on occasion, including the center representatives. The meetings allow for quick actions and reactions to scientific developments, initiate new cooperations, and are central to the collaborative spirit of the Topic.

Infrastructures

The first-class Helmholtz research infrastructures of the Research Field *Matter* are essential for the success of our Topic (see also Chapter 3.2). Complementary MT-ARD test facilities provide access to a wide range of beam parameters and technologies: femtosecond electron bunches (ARES at DESY, FLUTE at KIT, plasma-based accelerators in ATHENA) to picosecond nanocoulomb beams (PITZ at DESY), large CW beam currents (tens of mA at bERLinPro at HZB), highest repetition rates and stability in storage rings (COSY at FZJ, KARA and cSTART at KIT), and heavy-ion beams (GSI). With ATHENA, a jointly developed distributed infrastructure for plasma accelerator experiments unites, expands, and complements the leading capabilities at the partner sites and the high-power laser and beam driver technology for the ST4 research program. In addition, the LK II facilities FLASH (DESY) and ELBE (HZDR) provide dedicated MT-ARD periods to significantly advance CW operation challenges, laser-based seeding techniques, and plasma wakefield acceleration. These “beam test facilities” are complemented by a suite of commonly used infrastructures, including expansive processing, clean assembly, and SRF testing for electron and ion accelerators. They comprise a full suite of test facilities for material sample tests, prototype cavity and module testing, and tests with beam, which are also pivotal for industry and university partnerships.

Opportunities and Risks

Our activities in the four Subtopics of MT-ARD are associated with a large portfolio of great opportunities with societal impact in scientific, industrial, and medical applications. However, they also involve a wide range of risks with varying levels of predictability with respect to the successful fulfillment of expectations. On purpose, the objectives of MT-ARD in PoF IV carefully balance high-risk, high-reward projects with evolutionary – and thus more plannable – technology development activities. On the one hand, pursuing different advanced concepts in parallel can have the risk to spread out available resources to activities that may not be equally successful. On the other hand, making selections too early carries the risk of missing opportunities. Regular reviews and possible redirections of parts of the program will guarantee a healthy balance between risks and opportunities (e.g. [ARD-2]). The MT-ARD management is aware that an efficient exploitation of the distributed facilities to realize these opportunities requires a careful coordination between the centers to fully exploit the unique potential provided by these facilities. These joint projects in the distributed R&D facilities strengthen collaboration and exchange between the centers, heavily outweighing any enhanced coordination effort.

The MT-ARD focus on compact accelerator technology may lead to a paradigm shift in accelerator applications with potentially large impact, e.g. through compact medical applications. These activities are clearly high-risk, but high-reward if successful. A particularly interesting opportunity lies in the possibility to merge novel concepts with established technologies, e.g. by using plasma-based injectors for storage rings or dielectric structures for beam manipulation in FELs. In parallel, we will evolve technology and methods for upgrading existing and planned accelerator facilities, relying on our unique infrastructures and know-how. Most prominently, the realization of efficient CW operation in the near future will have a strong impact on the upgrade path of existing large-scale facilities; the associated risk of failure can be considered low. In contrast, the development and implementation of novel superconducting materials in large-scale facilities for cost-effective 4.2 K operation of SRF systems is a long-term activity, whose successful completion is a formidable challenge and thus difficult to predict. Several developments such as diagnostic and timing systems for sub-femtosecond precision or high-field fast-ramped superconducting magnets are of increased risk, but bear the potential to become game changers in accelerator science and subsequently in all Programs of the Research Field *Matter*.

2.2.2. Topic Detector Technologies and Systems

Executive Summary

MT-DTS will conceive and develop cutting-edge detector technologies and systems to keep the Research Field *Matter* at the forefront of scientific discovery, to exploit the scientific potential of our current and future facilities, and to explore novel detection methods that promise to open entirely new research directions in *Matter*. MT-DTS will in particular strive to push the physical limits of space, energy, and time resolution, both in principle and in concrete systems, ready for experiment. In addition, MT-DTS will develop innovative detector and data acquisition concepts to cope with the extreme data rates and adverse environmental constraints that are typical for experiments in the Research Field *Matter*.

Strategy

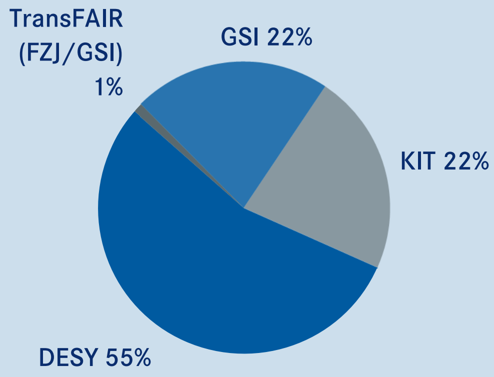
Our strategy builds on our very successful approach of PoF III, in which we combine fundamental R&D into sensors and detectors with a strong emphasis on system development and integration. We will explore, develop, and adapt technologies of interest for detector instrumentation. We will implement technologies in advanced demonstrator systems and characterize them in realistic experimental environments. We do this in close interaction with the other MT Topics and Programs in the Research Field and beyond, so that our demonstrators and technologies advance research in MU and MML. Our success depends critically on the close collaboration between physicists and engineers, both within the Program MT and with MU and MML and beyond.

Facts and Figures

Participating centers:
DESY, GSI with HI Jena and HIM, KIT, FZJ and GSI through TransFAIR[2]

Spokespersons:
Marc Weber (KIT),
Silvia Masciocchi (GSI)

Core-funded scientists: 54 FTE (2021)
Core-financed costs: 12,5 MEUR (2021)



Contributions of the centers to Topic MT-DTS:
Total core-funded FTE in 2021

Strategic Goal of the Topic

MT-DTS will develop cutting-edge detector technologies and make them available to the Research Field through demonstration in complete systems. For PoF IV, we have identified two main thrusts for our research: combining precision space, time, and in some cases energy resolution in one detector system with resolutions approaching the limits of detector physics; and coping with the deluge of data modern detectors provide.

The first thrust comprises several research directions: We will significantly expand our work on superconducting detectors for ultimate energy resolution, and in particular make a large effort to ease access to these high-tech systems. In addition, we will concentrate on fast, high-resolution solid-state systems, with high quantum efficiency covering the entire electromagnetic spectrum, and spatial and time resolution of so far unreached precision. We are

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2 TransFAIR denotes the activities of the FZJ Institut für Kernphysik (IKP), which are planned to be transferred to GSI during PoF IV.

convinced that meeting the challenge of extreme data requires a radically new solution. We will strive to establish silicon photonics as a pioneering technology for the transmission of huge detector data streams.

In addition to these most prominent and potentially paradigm-changing goals, MT-DTS explores a rich spectrum of complementary technologies relevant to detector instrumentation in the Research Field *Matter* and beyond. We will for example provide most powerful custom data acquisition (DAQ) platforms for real-time processing, visualization, and analysis of these data. We will actively scout technologies and identify promising technologies that have not yet emerged or are not yet a priority today. We consider such a forward-looking active process to be of key importance to maintain leadership in our field and to remain attractive for top scientists.

We address detectors for particle, hadron, and nuclear physics, photon science, astroparticle physics, and beam diagnostics, and explore applications such as e.g. medical applications and more. We closely cooperate with MT-ARD and MT-DMA, and with the two other *Matter* Programs MU and MML. MT-DTS is structured in the three Subtopics *Detection and Measurement* (ST1), *System Technologies* (ST2), and *Science Systems* (ST3). Intentionally, these three Subtopics span the full range from fundamental R&D into sensors to complete systems for specific scientific applications.

To respond to the ever-increasing need within *Matter* for cutting-edge detector technologies, we intend to significantly enhance our infrastructure. A core element of this effort will be the establishment of the Helmholtz Distributed Detector Laboratory (DDL), through which new and cutting-edge competences developed at specific centers will be made available to the entire community. This will only be possible if funds to build this infrastructure will be allocated [DTS-1].

MT-DTS **ST1** is dedicated to the development of sensors and the closely related custom integrated circuits (ASICs). While MT-DTS excels in many areas of sensor research, we will focus on the key challenges and on areas where we see opportunities for revolutionary changes and maximum impact.

We will significantly expand our activities in the area of superconducting sensors in order to approach the ultimate limits of energy resolution. We will strive to make the full range of X-ray energies accessible, in particular the notoriously difficult regions of very soft and very hard X-rays, where standard silicon sensors are inadequate. Thus, the development of back-illuminated, thinned, and post-processed silicon sensors as well as high-Z semiconductor sensors is a high priority. We will also continue our R&D on radiation-hard sensors for applications with extreme photon or particle fluence.

The integration and data processing technologies required to turn sensors and ASICs into a complete system are the leitmotif of MT-DTS **ST2**. In ST2, we will develop engineering techniques for the construction of highly integrated detector modules and their subsequent assembly into larger structures with, in total, millions to billions of electronic channels. These assemblies may face rigid constraints and have numerous, and sometimes competing, mechanical, electrical, and thermal functions. Our research covers high-density interconnect and packaging technology, automatic assembly methods, thermomechanical simulations, innovative cooling systems, assembly of light-weight carbon-fiber structures, materials research, and more.

Some *Matter* experiments equipped with our detectors represent the most intense local sources of (digital) raw data anywhere. Coping with these extreme data streams is another focus of ST2. We will address the challenge of transmitting the data from the detector to back-end systems with silicon photonics. We also pursue the theme of multi-wavelength readout for superconducting sensors with microwave frequency combs, where MT-DTS research is world-leading to date. MT-DTS will design and explore powerful heterogeneous data acquisition and processing platforms. The breadth of the MT-DTS application fields and the concerted design of readout ASICs in ST1 and data processing systems in ST2 enable MT-DTS to exploit many synergies. An additional asset is the creation of MT-DMA and the anticipated close collaboration with this new Topic on the algorithms run on our DAQ platforms.

MT-DTS **ST3** is designed to set up specific projects to test the most advanced technologies in full demonstrator systems, with science application being the ultimate performance test. We strive to combine technologies from ST1, ST2, and beyond in a given demonstrator system in order to use resources effectively and enhance demonstrator performance and impact. The concrete systems, which will change over the course of PoF IV, will result from an intense interaction with ST1 and ST2 in MT-DTS and with the two other *Matter* Programs. As a result of this process, MT-DTS remains coherent, dynamic, and flexible. The operation of complete prototype systems in our test facilities and experiments will also, as a test bench, foster the development of simulation tools within MT-DMA towards "digital twins" (see MT-DMA ST3).

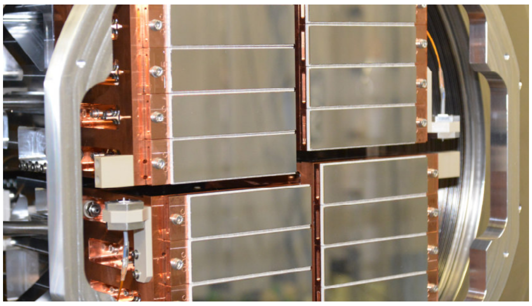


Figure 8: Sensors and ASICs of the AGIPD detector at the European XFEL (from DTS-ST1).

Competences

MT-DTS has a strong record in conceiving, designing, delivering, and operating key instruments for *Matter* experiments and facilities. With the conception of the Program MT and its Topic MT-DTS, the visibility of our research has markedly increased, collaboration between centers has become closer, and detector instrumentation has blossomed. Key assets that help MT-DTS to remain innovative and successful in achieving its goals are its broad technical competence, a diverse and interdisciplinary blend of permanent staff of physicists, engineers, and technicians, and a rich technical laboratory infrastructure.

Many of our scientists and engineers are not only experts in technologies, but have been closely involved in one of the two other Programs in *Matter*. We consider this a key strategic advantage, which ensures that our competence maps the requirements of the science programs in MU and MML.

MT-DTS excels in sensors. We are coordinating and leading the investigation of radiation-hard silicon sensors for photon science [24] and particle physics [25] and operate irradiation facilities. In collaboration with industrial partners, we brought high-Z sensor technology to a point where it is fit for use in experiments [26]. CMOS sensors are becoming a key part of our portfolio; for example, our pioneering HVCMOS sensor demonstrators have reached maturity and fulfill the stringent requirements of the high-luminosity LHC (HL-LHC) upgrades [27]. We have been extremely productive with numerous ASIC and system developments for a variety of applications. These include the MHz-rate burst imaging detectors AGIPD [28] and DSSC at the European XFEL, the Belle II vertex detector [29], picosecond-resolution Cherenkov light and time-of-flight detectors [30], beam diagnostic instrumentation [31], and medical imaging. The creation of MT-DTS has also propelled our DAQ competence. The MT-DTS DAQ platform, developed jointly by several centers [32], forms the foundation for the rapid development of high-performance DAQ systems with data rates of several GB/s and with latencies down to a few microseconds [33]. This platform has enabled unique developments such as the modular scientific camera system UFO, the ultrafast waveform sampling system KAPTURE for THz detectors with picosecond resolution and GHz repetition rates [34], and the custom line camera KALYPSO for single-shot electro-optical bunch profiling with 10 million frames per second [31] (both are a cooperation between MT-DTS and MT-ARD). By integrating GPUs in DAQ systems, we have accelerated data processing for applications such as tomographic reconstruction by orders of magnitude [35]. We are advocating and pioneering silicon photonics for data transmission systems in detector instrumentation [36]. Our multiplexing technology for readout of many-pixel superconducting sensors has attracted great interest [37][38]. MT-DTS R&D on electronic packaging, novel materials, low-mass support structures, and innovative cooling concepts [39] have helped to pave the way for large-scale detectors for the HL-LHC upgrades and the FAIR experiments [40].

Next to its competence in advanced technologies, MT-DTS is a leader in systems development. Here, our proximity to the users and science applications in MU and MML is a major asset. We are able to model and evaluate complex detector designs with a rich set of refined and realistic simulation tools. MT-DTS has proven to react nimbly to the requirements of experiments and to provide fast turnarounds in response to ever-increasing user demands. Successful demonstrator systems also form a key link in the innovation chain. For example, the Helmholtz Cube "Lambda" detector developed within MT-DTS [26] has been commercialized by the spinoff company X-Spectrum. Our system competence is demonstrated by a variety of projects: the delivery of the aforementioned AGIPD [41], the DSSC [42] detectors, the KAPTURE and KALYPSO systems [31][34], the production of a large fraction of the CMS vertex detector upgrade and our central role in the upgrades of the ATLAS and CMS tracker systems, the upgrade of the ALICE time projection chamber, the integration of multi-pixel high-resolution superconducting sensor systems for high-precision QED studies at FAIR [43], and the development of the mDOM Cherenkov detector modules recently selected for the IceCube-Gen2 upgrade. Our expertise in system integration has enabled the establishment of a game-changing technology for highly granular calorimeters, where we are recognized as world-leading experts [44].

Objectives and Approach

ST1 – Detection and Measurement: ST1 investigates sensors, as an essential building block of any detector system, and the intimately linked custom readout circuitry (ASICs). We will push the development of advanced **silicon sensors for greater time, energy, and position resolution**. Prominent examples are low-gain avalanche diodes (LGADs). They have already attracted great interest as particle tracking and timing detectors in high-energy physics. LGAD devices provide a large signal, excellent time resolution of 20–30 ps and potentially a spatial resolution down to 20 µm. This would enable fully four-dimensional tracking detectors of unprecedented performance [DTS-2, DTS-3]. Enhanced lateral drift sensors (ELADs) promise improved spatial resolution by increasing charge sharing. This technology has high potential, and provided the production technology can be established, it could be an attractive sensor choice for future collider detectors. Development work in MT-DTS on LGADs, ELADs, and other silicon sensors includes sensor design, R&D on the processing of these devices with several industrial partners, prototype production, and characterization in the laboratory and at test beam facilities.

We will develop infrastructure for **thinning and post-processing silicon sensors** to make these technologies readily available for tailoring sensors to different applications. In particular, back-illuminated CMOS sensors and pixelated LGADs with thin entrance windows could greatly improve detection of soft X-rays in photon science. This, along with continued collaboration with industry to develop **high-*Z* sensors** for hard X-rays, would make it possible **to cover the full spectrum of X-ray energies** at synchrotron and FEL beamlines [DTS-6].

We observe a surge of opportunities for **superconducting sensors** across several fields of research. For instance, metallic magnetic calorimeters (MMCs) offer uniquely high energy resolution, which makes them ideally suited for applications in neutrino physics, dark matter searches, spectroscopy, astrophysics, atomic physics, molecular physics, and more. Together with the Universität Heidelberg, we will establish superconducting sensor production capacity in MT-DTS.

During PoF III, **depleted monolithic CMOS sensors** have reached a level of maturity that has made them a viable choice for future particle, hadron, and nuclear physics detectors. They will also find application in astrophysics and photon science. Our R&D will address the ever-increasing challenges of improving granularity, timing, data rate, and radiation hardness. This development will require the expertise in both sensor development and integrated-circuit design available in MT-DTS.

The way to more in-pixel functionality in both monolithic CMOS detectors and hybrid pixel detector ASICs is to use state-of-the-art deep sub-micrometer processes. Exploring recent nanometer CMOS technologies is therefore a main activity in ST1, and we will strive to take leadership in this area. This includes the study of both **deep sub-micrometer mixed-signal** and **fully-depleted silicon-on-insulator (FD-SoI) processes**. In addition, we will explore BiCMOS SiGe technology for applications requiring extremely high-speed operation. All the aforementioned processes have the potential to significantly push the limitations of the current technology and will be essential for the next generation of detector systems in all of *Matter*.

To fulfill the needs of diffraction-limited synchrotron sources and future CW FELs, an **ultrahigh continuous frame rate detector with small pixel size** is required. We will employ 65 nm CMOS nodes to develop the technology for low power in pixel ADCs as well as for very high-speed data transceivers [DTS-4]. While these developments are directly driven by the needs of future light sources, they are also generic and widely applicable.

Supreme time resolution is an important requirement for a wide range of experiments. To address this challenge, we plan families of ASICs realized in either deep sub-micrometer CMOS or BiCMOS SiGe technology. Combined for example with LGADs, these ASICs will allow dedicated four-dimensional tracking in particle physics experiments and detection of particles such as electrons and ions in other fields (e.g. mass spectroscopy experiments). Similarly, to expand our leadership in advanced beam instrumentation, we will develop **ASICs for pixelated THz sensors**, again allowing combined spectral, timing, and spatial resolution.

Our applications of **BiCMOS SiGe technology** include the readout of metallic magnetic calorimeter arrays, noble-gas time projection chambers, and terahertz detectors for photon science. By exploiting the combination of high speed and large voltage swing, we will also develop an advanced modulator driver for the terabit-scale data link developments pursued in ST2 [DTS-5]. Semiconductor foundries are increasingly offering silicon photonics in deep sub-micrometer CMOS processes, making it possible to embed optical components in readout chips. We will extend our developments in this area, in order to closely integrate high-speed optical data transmission with front-end detector electronics.

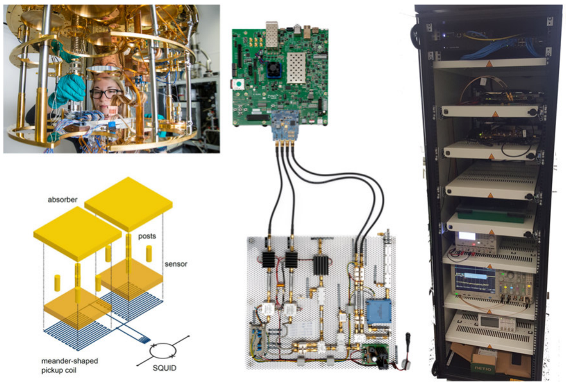


Figure 9: Cryogenic detector system with open cryostat, MMC sensor, mixed-signal readout electronics and rack (from DTS-ST2).

MT-DTS also has long-standing experience in developing TDC ASICs, which led to successful time-of-flight and Cherenkov light detector designs for STAR and FAIR as well as large-dynamic-range readout ASICs for electromagnetic calorimeters and gaseous detectors. Building on this experience, we will continue to improve this technology by using new architectural concepts and recent nanometer technology nodes.

The exchange of design experiences, technologies, and analog and digital blocks for ASICs is a key strength of MT-DTS. We have already established, and will further strengthen, the network between physicists, designers, and engineers across the different research centers. This will be augmented by regular meetings and workshops focusing in particular on ASIC design to further foster common projects.

ST2 – System Technologies: ST2 investigates optical data transmission, massively parallel data processing, and advanced system-engineering technologies. In these areas, we have identified technologies that are essential for future detector systems and where we are aiming for technological leadership.

Silicon photonics offers the potential to greatly increase data transfer rates for detector readout, to combine multiple readout channels, and to reduce power dissipation in the front-end. Our current competencies in photonic chip design will be substantially increased. We will establish a design flow including design, simulation, and layout generation for the fabrication of radiation-hard wavelength division multiplexing (WDM) transceiver chips with dozens of channels [DTS-5]. Using technologies such as segmented modulators easily enables advanced modulation formats, resulting in more than a terabit bandwidth per fiber and reduced passive material in the detector volume. Achieving the targeted number of WDM channels and their respective bandwidth requires advanced drivers and integration into ASICs as well as advanced electrical packaging technologies. Furthermore, alternative, multiplexer-free WDM concepts based on ring modulators will be investigated. The advantages of this new approach are much reduced chip sizes by avoiding distinct multiplexers, smaller modulators, and lower driving voltages. Laboratory infrastructure to characterize and integrate photonic systems will be established and a demonstrator project will be realized within ST3 [DTS-16].

A major focus of DTS in PoF IV will be the development of cryogenic sensor systems. Cryogenic sensors offer uniquely high energy resolution, but so far they only provide a small number of pixels, thereby limiting spatial resolution or detection rates. Advanced multiplexing techniques will solve this problem and allow for the **readout of cryogenic sensor arrays** with hundreds or even thousands of pixels. We plan to develop dedicated readout electronics for microwave SQUID multiplexed readout of large pixelated cryogenic sensor arrays [DTS-7]. We will support the application of these technologies in a highly sensitive keV-scale sterile-neutrino experiment using MMCs in a many-pixel configuration (see ST3 and [DTS-13]). We will also exploit flux ramp modulation and multiplexing in the baseband to improve linearity and resolution for experiments with fewer pixels. To support this R&D, we will create a test center for cryogenic readout systems.

For experiments with extremely high data rates, we will design and assemble a distributed real-time data processing system with a high level of software abstraction in order to **provide scalable computing performance for DAQ systems**. Major advances are expected in commercial components such as FPGAs, CPUs, and GPUs. Industrial communication technologies are likewise continuously improving. It is a major challenge to ensure that these technologies can be adopted for efficient and powerful real-time data processing in order to exploit the full scientific potential of most experiments. For more and more experiments, storing all the raw data will not be technically and economically viable. Instead, sophisticated algorithms are required to select the information of prime interest and reduce the data volume on the fly. Dramatic advances in data processing algorithms are anticipated and required during the upcoming funding period. We aim to advance continuous data processing by an order of magnitude. Even for complex algorithms, we expect to cope with data streams of terabits/s [DTS-10].

To enable very high integration density and billion-pixel detector systems, ST2 will complement the sensor and ASIC development in ST1 with **advanced packaging and assembly technologies**. We will explore and adapt under-bump metallization (UBM) and through-substrate via (TSV) processes, with a central goal being the development of edge-less systems. We will also develop new micromachining, flip-chip, and planarization techniques for cryogenic and high-Z sensors. In-house processes will ensure rapid and tailored assembly of advanced detector systems. These processes will also be the foundation for the development of 3D interposer package technologies for future detector generations [DTS-9].

Microfabrication will allow us to bring the cooling media closer to the actual heat source. This will make front-end cooling more efficient and also reduce the amount of passive material, which is a primary requirement in particle tracking. We will investigate and use additive manufacturing, which is now commercially available for ceramics and metals, and continue to explore novel materials for their use in detector mechanics and cooling. We plan to exploit manufacturing trends and processes currently available in industry. To achieve that, we commit to enhancing our expertise in these fields and to providing the best thermomechanical design for future applications [DTS-8].

ST3 – Science Systems is designed to demonstrate detector systems for our four main applications fields: particle, hadron, and nuclear physics, photon science, astroparticle physics, and beam physics. While there are distinct system requirements for each application, they share common system-engineering challenges, and overcoming these is the very essence of MT-DTS and ST3.

One main theme of ST3 activities during PoF IV will be the integration of large, **highly granular pixelated systems** optimized for their respective applications, such as photon science, tracking in nuclear and particle physics, and UV astronomy. Common integration challenges of these systems include power management, end-to-end handling of highest data rates, efficient system control schemes, as well as handling and precisely mounting ultra-thinned large sensors and minimizing material budget while maintaining temperature stability and uniformity.

The planned CW operation of the European XFEL will demand imaging detectors akin to today's AGIPD or DSSC, but with almost two orders of magnitude higher continuous readout speed (100 kHz frame rate) and ideally with even larger imaging area and smaller pixels. A similar demand arises from experiments at future diffraction-limited storage rings. Such detectors are essential to bridging the gap between molecular and macroscopic scales, and they will require a new generation of hardware in every stage of the readout chain. We intend to demonstrate the feasibility with a hybrid pixel system, initially in combination with silicon sensors [DTS-16].

The combination of extreme granularity – and thus excellent spatial resolution – with sub-nanosecond timing resolution in one system is promising to induce a paradigm change in particle and heavy-ion physics detectors. We will demonstrate these capabilities in a silicon beam telescope system that simultaneously provides ultrafast timing, unprecedented spatial resolution, and ultralow X/X_0 [DTS-12].

MT-DTS will significantly expand its expertise in **cryogenic detector systems**. They hold great potential for a wealth of applications, but operating multipixel systems at temperatures of tens of millikelvins is challenging, especially if the sensor cannot be fully enclosed in a cryogenic environment.

Figure 10: Four-layer beam telescope system with LGAD ultrafast silicon detectors installed at GSI (from DTS-ST3).

We will first evaluate a 1k-pixel MMC array for a future experiment searching for keV-scale sterile neutrinos, with tritium-loaded MMC absorbers as the neutrino source. Here, the sensor is fully enclosed in a cryogenic environment. We will then operate a 1k-pixel MMC for detection of hard X-rays from heavy-ion storage rings such as CRYRING in a large-aperture assembly [DTS-13]. Furthermore, we will assemble cryogenic detector systems based on SQUID technology for non-destructive detection of lowest beam currents at hadron accelerators and storage rings.

The range of applications and challenges addressed by MT-DTS for MML and MU is very broad, sometimes requiring radically different sensor approaches. For example, timing and tracking detector systems for particle and heavy-ion physics must be **extremely radiation-hard**, and detectors for remote-site deployment or satellite applications in astroparticle physics must be **extremely robust**. Thus, the verification of reliability and performance of the entire system in its intended environment and scientific context through science-grade prototype systems is indispensable.

One example is gaseous detectors in square-meter-sized assemblies for particle tracking at extreme fluxes. The feature size necessary to limit both the occupancy and the number of channels hits a gap between the feature size scales naturally available on printed-circuit boards and in silicon lithography. Development and stable operation of large assemblies combining 50 µm-sized readout channels, integrated gain, and less than 0.1% X/X_0 per plane will be demonstrated.

In cooperation with MT-ARD, a THz detector system combining spatial, spectral, timing, and polarization information with 500 Mfps readout will be developed. It exploits emerging THz devices that provide a bandwidth-programmable frequency comb, usable as resonant detector as well as a pixelated emitter. The development builds on key MT-DTS competences – from LGAD sensors to custom ASICs, interconnects, DAQ, and online data processing of enormous data streams. The system will enable novel beam diagnostics and phase-space-regulating accelerator control [DTS-14].

Highly granular SiPM assemblies become more and more attractive as an ultracompact and high-spatial-resolution alternative to classical PMTs for applications such as calorimeter readout, scintillating-fiber particle trackers, or hadron therapy. Their specific challenges include a requirement for high temperature stability to avoid gain fluctuations. A new 5D calorimeter prototype will utilize SiPM readout for few-nanosecond timing of interactions [DTS-15].

Detector systems utilizing Compton scattering for imaging or polarimetry fill a special niche both in storage ring atomic physics and in MeV astronomy. Their particular challenge lies in combining high granularity and fine-tuned coincidence logic with radically minimized passive material between sensor layers to avoid missing interactions. A small, lightweight prototype is under development, intended for a CubeSat mission that could, at only 5 kg, surpass the 1 MeV sensitivity of NASA's Compton Gamma Ray Observatory. A larger array, built from Ge and Si(Li) double-sided strip detectors, is optimized for hard X-ray polarimetry and aims at precision QED tests at GSI and FAIR [DTS-11].

The links we establish in ST3 across a wide range of scientific application fields, engineering disciplines, and centers play a key role in disseminating new technologies expediently and to the highest benefit for science. Early recognition of multipurpose enabling technologies is key to maximizing synergy effects within MT. In order to maximize cross-fertilization, ST3 will foster a climate of open exchange where different systems and applications can optimally benefit from experience gained throughout MT-DTS and beyond. ST3 will monitor demonstrator progress and organize peer-review-style feedback. We will encourage discussing open opportunities with a broad range of experts and organize topical workshops with Helmholtz and international experts to conceive or promote specific detection concepts.

Expected Results

The following Table 2 shows important milestones well suited for monitoring the progress of our Topic:

Table 2: Milestones of the work program for the Topic MT-DTS

	Milestone	Subtopic	Year
DTS-1	Establish and commission the Distributed Detector Laboratory	ST1–3	2025
DTS-2	Establish availability of sensors with high spatial (20 µm) and time resolution (20 ps) for charged particles	ST1	2024
DTS-3	Develop a readout ASIC family for combined space, time, and energy measurement	ST1	2024
DTS-4	Develop a high-rate pixel readout ASIC for diffraction-limited synchrotron sources and future FELs	ST1	2025
DTS-5	Establish silicon photonics system components for optical data transmission	ST1, ST2	2025
DTS-6	Establish availability of high-performance sensors covering the entire X-ray spectrum	ST1	2026
DTS-7	Realize scalable readout technologies for pixelated cryogenic detector systems with > 1000 channels	ST2	2022
DTS-8	Validate integrated microchannel cooling structures	ST2	2023
DTS-9	Establish packaging technologies for hybrid detectors with non-Si materials and 3D structures	ST2	2024
DTS-10	Assemble an intelligent terabit data acquisition and processing platform for advanced algorithms	ST2	2027
DTS-11	Evaluate the performance of a Compton detector in the high-keV to low-MeV regime	ST3	2022
DTS-12	Assemble a silicon beam telescope system demonstrating at the same time ultrafast timing, high spatial resolution, and ultralow X/X_0	ST3	2024
DTS-13	Operate routinely a 1k-pixel cryogenic MMC sensor array for precision QED tests at CRYRING	ST3	2025
DTS-14	Provide a pixelated THz detector combining spectral, space, and time measurement for beam diagnostics	ST3	2025
DTS-15	Bring into operation a highly granular 5D (position, time, energy) calorimeter prototype with SiPM readout	ST3	2026
DTS-16	Demonstrate a hybrid pixel system capable of matching CW FEL bunch rates with advanced (optical) data transmission	ST3	2027

Synergies and Collaboration

The collaboration between the groups and the centers involved in MT-DTS is traditionally strong. In addition, we work closely with international partners in many projects. Cooperations exist with essentially all leading institutes in our fields of research.

MT-DTS has successfully established strong collaboration with MT-ARD in beam diagnostics, where we are world-leading, and elsewhere. We will now expand joint activities with both MT-ARD and the new Topic MT-DMA, starting with real-time applications of deep-learning methods in accelerator controls. We have already created the innovation pool project

AMALEA to initiate this combined effort. The development of real-time algorithms running on custom MT-DTS hardware platforms, combined with start-to-end simulation and computing center integration by MT-DMA, offers many synergies.

The links between MT-DTS and the Programs MU and MML are very strong, and the strategies of all *Matter* Programs are closely aligned. Many MT-DTS staff members work part-time on experiments or projects within MU and MML, thus close exchange and communication are automatically guaranteed.

The work in MT-DTS is supported by a lightweight organizational structure. Each Subtopic is headed by two coordinators from different centers. Subtopics, in turn, are structured into work packages, led by two coordinators. The demonstrator projects in ST3 form an effective link across MT-DTS and into MT-DMA as well as MU and MML, combining advanced sensors, ASICs, and system components into full working units delivering data for first scientific applications. Established and effective MT-DTS management tools include regular phone conferences and meetings of the MT-DTS executive board and the work package coordinators. There are dedicated topical meetings and workshops, complemented by the successful and high-profile MT annual meeting of all Topics. All of this allows us to monitor progress, optimize the use of resources, identify promising research directions, and act expediently.

Infrastructures

While MT-DTS does not operate LK II infrastructures, cutting-edge and in several cases unique infrastructures operated by professional and permanent staff are a distinct asset of MT-DTS. These infrastructures include test beam facilities, irradiation centers, electronic interconnect and packaging centers for building cutting-edge silicon sensor assemblies, surface-mounted device facilities for building and testing complex electric board assemblies in house, microwave and radio wave detector characterization labs, etc.

In order to strengthen the long-term quality and impact of our research, we strive to implement the Helmholtz Distributed Detector Laboratory (DDL). We have thus compiled a ~30 million euro proposal for a large-scale investment to substantially expand the high-technology infrastructure of MT-DTS. In doing so, we have delivered on the recommendations that each MT-DTS partner received in their scientific evaluation. Key elements of the DDL are post-processing of silicon sensors, fabrication of superconducting sensors, preparation and 3D structuring of bulk semiconductors, a high-Z semiconductor facility, and test beam infrastructures.

Opportunities and Risks

By placing the focus on several paradigm-changing technologies, we anticipate creating huge opportunities. Some of our research areas, such as 4D sensors or silicon photonics, would qualify as high-risk, high-impact research, enabling experiments that may be realized only beyond PoF IV. To mitigate risk and maximize opportunity, we sometimes address experimental challenges with two alternative technologies. In charged-particle tracking, for instance, we pursue both CMOS and LGAD sensors. Fortunately, we are not particularly dependent on single vendors of sensors, ASICs, or digital hardware.

By offering exciting challenges and the opportunity to apply cutting-edge technology and enable forefront science in an international, diverse, and interdisciplinary environment, we keep attracting young talents to MT-DTS. However, the competition with lucrative industry positions in the technology sector and elsewhere remains a constant challenge.

Several of the technical solutions we envisage face fierce competition. Here, the breadth of our science applications provides maximum opportunities to quickly introduce a given technology into experiments. For instance, silicon photonics or monolithic CMOS sensors might first succeed in photon science, which will provide valuable insights and pave the way for applications elsewhere. The ST3 demonstrator projects enable us to mitigate risk by testing technologies early in a realistic environment, to introduce them into applications quickly, and thus to provide maximum benefits to MU and MML as well as MT-ARD and MT-DMA.

The establishment of the DDL will create great opportunities for MT-DTS. While it should be noted that the presented research program is not based on the realization of the DDL, its installation was strongly recommended in all scientific evaluations, and a delay in this important endeavor clearly represents a significant risk.

2.2.3. Topic Data Management and Analysis

Executive Summary

MT-DMA as a Topic will address a cornerstone of the scientific process within the Research Field *Matter*. It will focus on the challenges of large-scale, high-rate data ingestion from large-scale facilities, experiments, observatories, and the accelerators themselves when looking at increasingly complex systems. MT-DMA focuses on and is driven by the data needs and challenges of the science within *Matter* and is thus complementary in its approach to the more generic research in the Research Field *Information*, with which it will collaborate closely. With the advanced capabilities of next-generation accelerators, observatories, light and neutron sources, and detectors, MT-DMA (i) builds modular platforms for data lifecycle management following FAIR (findable, accessible, interoperable, and reusable) principles at world-leading scales, (ii) enables the extraction of knowledge from data by developing and applying advanced methods such as machine learning and optimal use of modern high-performance hardware, (iii) creates “digital twins” of experimental infrastructure for comprehensive start-to-end simulation, and fosters near-real-time feedback and optimization of experimental conditions during data taking.

Strategy

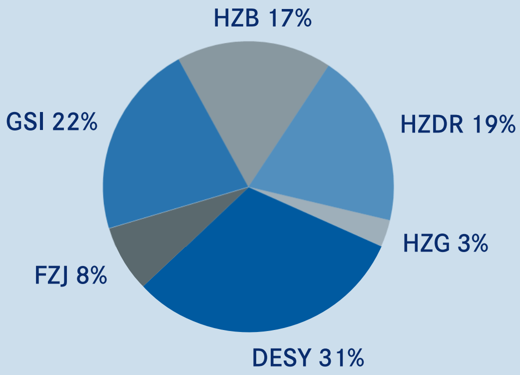
Our strategy builds on the long-term expertise within the Helmholtz centers in handling the large-scale data related to the research and user facilities within *Matter*. For the first time, the Helmholtz centers from particle, hadron, ion, and nuclear physics as well as photon and neutron science will join their efforts on digitalization in a single, concise Topic, thus creating new synergies, common practices, and solutions. MT-DMA’s long-term vision is the digitalization of the scientific process over the entire Research Field *Matter*. As a Program Topic, MT-DMA will be a unique ingredient of and single point of contact for the digitalization strategy of the Helmholtz Association and national and international digitalization strategies. MT-DMA will look into the future of data acquisition and analysis, exploring the use of exascale interactive supercomputing and quantum computing for modeling complex systems and solving future data evaluation and analysis tasks.

Facts and Figures

Participating centers:
DESY, FZJ, GSI with HI Jena, HZB, HZDR, HZG

Spokespersons:
Michael Bussmann, HZDR
Volker Gülzow, DESY

Core-funded scientists: 50 FTE (2021)
Core-financed costs: 8,3 MEUR (2021)



Contributions of the centers to Topic MT-DMA:
Total core-funded FTE in 2021.

Strategic Goal of the Topic

MT-DMA has been set up as a Topic in the Program MT with the goal of addressing the common challenges in high-level knowledge extraction from data produced at the large-scale facilities and experiments within the Research Field *Matter*. With MT-DMA, we want to develop modular, interoperable solutions combining complex and advanced compute methods with expert knowledge from the scientific fields, and ensure easy and broad access to these solutions. We will build on the work already done in *Matter* within MU, MT, and MML, bring the different activities together, and push them forward coherently.

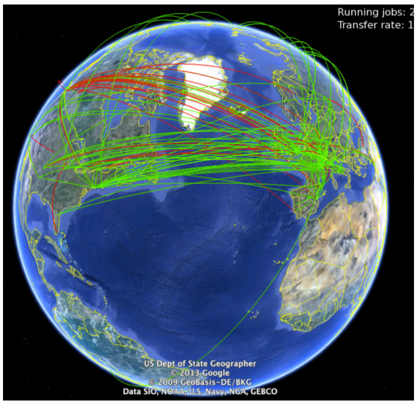


Figure 11: The WLCG (World-wide LHC Computing Grid) connects analysis and simulation sites worldwide, with over 100 PB of data processed in 2018. The picture visualizes the flow of information in the WLCG network (from DMA-ST1).

We face challenges at several levels: Data of increasing complexity are produced at larger and larger rates and volumes. We need to develop and provide means to reduce the data volume close to the data source by typically several orders of magnitude in order to make the data problem tractable. We need to develop and provide means and methods to extract knowledge on complex systems in a large variety of scientific areas from data and make these methods accessible to a broad range of users ranging from individuals to large research groups. We finally need to develop and provide ways to store the data alongside its metadata in a findable, accessible, interoperable, and reusable way (FAIR principles), and do this in a sustainable system so that data are accessible also after the end of experiments. We will work for and with all of the Research Field *Matter*, as part of an overall strategy to push the digital methods into all aspects of research in *Matter.*

With MT-DMA, we will address these challenges through investment in infrastructure, in people, and in knowledge. A key asset that we rely on heavily is the close interaction of computational and data science experts and domain scientists. Through its organization as a part of MT, MT-DMA is naturally tightly interfaced to the other Programs MT and MML, and profits from the close connection to the other two MT Topics, MT-ARD and MT-DTS. This integration ensures that the priorities in MT-DMA are coordinated with the goals in MU and MML, and are firmly rooted in the scientific agenda of *Matter*. MT-DMA as a Topic will profit enormously from the great store of know-how and experience already present in *Matter*. It is this strong basis that allows us to formulate the ambitious and broad program in MT-DMA that we will outline below.

As a Topic in the Research Field *Matter*, MT-DMA complements the broader, more generically driven research done in the Research Field *Information*. In addition, MT-DMA is a part of the overarching digitalization strategy of the Helmholtz Association and of national and international digitalization efforts to ensure synergies and complementary development and successful application of digital solutions to the needs of the Research Field.

The three Subtopics of MT-DMA reflect this strategy:

The Matter Information Fabric (ST1) is driven by a holistic view of data analysis at large-scale facilities. It focuses on building modular, interoperable, and reusable solutions to set up complete data lifecycle platforms that can be adapted to the needs of specific facilities and user communities. A key requirement is that they are scalable with increasing data rates and volumes. This platform will give the users easy access to the data at a variety of levels, from raw data at the detector to highly processed data ready for long-term storage. This will support and ease the process to transform data produced in the Research Field *Matter* into knowledge that follows the FAIR principles. To this end, MT-DMA can build on a broad set of experience already available in *Matter.*

The Digital Scientific Method (ST2) fosters the development, exchange, and use of advanced computing, data analysis methods, and algorithms throughout *Matter*. We want to develop common solutions usable by diverse communities. We intend to enable non-expert users to access modern computing tools. Examples of such systems are highly parallel, high-throughput methods for data analysis and simulations usable with modern heterogeneous computing hardware, high-throughput interconnects, and large-scale storage solutions. On the algorithmic level, we will research advanced methods for simulations and data analysis. On the technological level, we will implement solutions in a scalable and forward-looking way. Examples for cutting-edge technologies that might change the way we perform data analysis in *Matter* are artificial intelligence, exascale computing, and quantum computing.

The Digital Experiment and Machine (ST3) connects concrete facilities and experiments with the methods developed in ST1 and ST2. Applications will include near-real-time applications in machine controls, fast feedback on data from experiments, or implementations of complete and complex simulation models of experiments or accelerators. In this way, ST3 pushes the implementation of digital methods in *Matter* and, at the same time, provides a test environment for the more generic developments mentioned above.

Communication and interaction with the users are an important goal of MT-DMA. The success of MT-DMA will rely to a large extend on close communication and constant exchange with the users. To facilitate this, a portal called **S4M** – for shared, scalable solutions for science in *Matter* – will be set up. S4M will give access to data and software repositories, best practices, tutorials, knowledge bases, and communication channels related to digitalization within *Matter*, and make use of and be interconnected with existing solutions within *Matter* and Helmholtz. The structure of the portal will be defined and its content will be identified [DMA-1], the portal will be put online [DMA-2], and all solutions of MT-DMA will be made available in a continuous manner until the end of the PoF IV period [DMA-3] and beyond. S4M will make best use of and interconnect with existing platforms within *Matter* and Helmholtz to minimize development and maintenance efforts while maximizing impact and interoperability with existing and upcoming infrastructures on the national, European, and international level.

Competences

The participating Helmholtz centers provide extensive know-how and internationally acclaimed expertise in developing and operating data lifecycle and analysis solutions for a large variety of experiments, especially large-scale facilities.

The World-wide LHC Computing Grid (WLCG) for example brings together 170 computing centers and provides storage resources of more than 100 PByte/year [45] for local and remote users from communities such as particle, hadron, ion, and nuclear physics. Large-scale data centers such as the FAIR Tier-0 and the upcoming IDAF will greatly expand existing resources and expand their service to more and different research fields. Large-scale facilities such as European XFEL, FAIR, ESS, CTA, HL-LHC, PETRA IV, BESSY VSR, BESSY III, and DALI will profit from the experience in digitalization gained at cutting-edge facilities such as LHC, PETRA III, BESSY II, FLASH, and ELBE and from the deep knowledge and experience gained from operating the WLCG for high-energy physics.

Computer science experts from the *Matter* centers are in constant contact with research communities and industry, for example in projects on data management [46][47][48], as part of standard committees [49][50][51], or as advisers to design future computing technologies [52]. These experts provide long-term support of strategic developments and implement advanced methods scalable with data rate, volume, and complexity for the needs of next-generation facilities [53][54][55]. They can build on an outstanding record of implementing and driving international, large-scale, community-based software projects, providing software stacks for exascale-ready simulations and high-throughput data analysis [56][57]. They design and provide next-generation infrastructures, workflows, standards, and enabling software [58][59][60][61][62] to the worldwide scientific communities [63][64][65][66][67][68].

The centers practice a FAIR and open-science approach, especially with large-scale on-site experiments open to users. Facilities provide accompanying computing and storage resources for all stages of the experiments: planning, simulation, data taking, online and offline analysis, data transfer, and archiving.

Both infrastructures and experts are well integrated in and collaborate with other national, European and global projects. Decades of experience are combined within MT-DMA, ranging from development and operation of control, feedback, and diagnostics systems for accelerators [69], beamlines, and experiments to exascale-ready simulations of advanced plasma accelerators and laboratory astrophysics [70], from hands-on experience in imaging with *in-situ* and *operando* measurements (e.g. tomography with synchrotron radiation/X-rays/neutrons/electrons/ions) and advanced 3D analytics to measurements of the dynamics of matter under extreme conditions or of the structure of biomolecules, or to on-site as well as distributed analysis and simulations of accelerators [71] for particle physics experiments.

MT-DMA solutions are developed and applied in close collaboration with domain scientists from MU, MML, and within MT, serving as a perfect ground for research and implementation of cutting-edge digital technologies and novel approaches in the context of data ingestion, controls, and feedbacks for accelerators, beamlines, detectors, and experiments.

Objectives and Approach

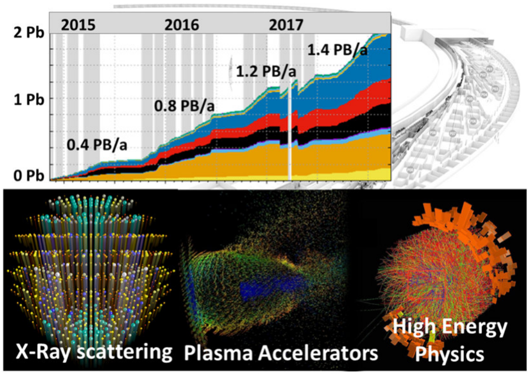


Figure 12: The complexity of data grows while the volume and rate increase due to the advancing capabilities of facilities (from DMA-ST1).

ST1 - The Matter Information Fabric: MT-DMA ST1 addresses the digitalization of large-scale infrastructures at all levels, identifying these levels across facilities and communities and defining clear interfaces between levels.

This includes especially the technological synergies between data lifecycle management, the setup and operation of distributed systems, as well as the principles of FAIR data management and open science, but also the synergies between the various facilities and communities within *Matter*. Major efforts will be devoted to large-scale, high-volume, high-rate scientific data lifecycle management and furthermore to a new, cross-discipline approach towards common solutions, based on accepted open standards.

MT-DMA ST1 will address both technical and organizational aspects of integrated solutions to manage the data deluge from high-data-rate instrumentation for the era when all facilities within the Research Field *Matter* will generate too much data for researchers to take home. Fast data vetoing and on-site data reduction (see MT-DMA ST2/3) within a limited time frame prior to downloading preprocessed data, or complete data processing performed where the data is stored, as in the WLCG, now serve as a role model for many facilities and research applications.

The current compute infrastructure needs to be transformed, however, such that real-time online analysis (see MT-DMA ST3) applying new and efficient algorithms (see MT-DMA ST2) is possible. This can be done by overcoming the online–offline storage division in the data acquisition and moving to data flow models (see MT-DMA ST3), optimally equipped with automated data analysis pipelines and *in-situ*, *in-transit* data reduction and analysis tasks.

Modern, distributed computing workflows with seamless and user-friendly remote access to distributed storage and compute resources developed in MT-DMA ST1 will surpass the classical funnel model of iterative data reduction and knowledge aggregation. They will instead be based on user portals for data analysis, visualization, control, and simulation, while new computing paradigms such as compute clouds, container orchestration frameworks, or big data analysis frameworks will be integrated into the infrastructure and into the workflows of the scientists.

Once data is sufficiently reduced for storage, it needs to be made available not only to users locally, but also to remote users. Efficient high-bandwidth data transport is paramount to this effort. Building on existing experience in technologies (dCache, XRootD, HiDRA), through participation in the Helmholtz Information and Data Science (IDS) platform HIFIS and infrastructure deployment (e.g. storage infrastructure in WLCG) as well as in EU projects such as the European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures (ESCAPE), MT-DMA ST1 will work on next-generation federated storage infrastructures such as data lake models as a promising option for future, large, federated collaborators.

Complementing the infrastructure for data storage, the infrastructure for metadata and source code management also needs to be developed to withstand the data deluge. This is in line with the adoption of FAIR principles and, where possible, open science. Collaboration between scientists will be leveraged by using common or federated data and metadata sources, common data formats and access methods, as well as common source code management methods, open source licenses, open standards, and data formats (see MT-DMA ST3).

In order to achieve an orchestrated shift in data analysis methodology and to identify possible synergies, the first step is to analyze the detailed requirements from the MT-DMA communities [DMA-4] through workshops and direct engagement with the different communities. A review of currently existing tools or tools being developed by other projects will be carried out and combined with a gap analysis in order to define a prototype of a data lifecycle management system in a distributed computing environment for all MT-DMA communities and centers [DMA-5]. Based on the system and tools identified, MT-DMA ST1 aims at developing a modular, generic, and open prototype that is portable across architectures and adaptable to community needs. The lessons learned from implementing and testing such a prototype will be subject to a review [DMA-6], thereby identifying the needs for a production-grade environment scalable to high data rate and large data volumes across the fields of *Matter*.

ST2 – The Digital Scientific Method: MT-DMA ST2 addresses data analysis methods, advanced algorithms, and new software technologies for knowledge extraction in the Research Field *Matter*.

This includes not only the design of efficient and scalable algorithms, but also the development of key software building blocks for ultrafast data processing on large-scale heterogeneous compute infrastructures, data reduction/knowledge extraction, synchronization of multiple data streams (multi detector setups also known as "event building"), transport services utilizing RDMA networks, container orchestration, and efficient binding to storage and network. These interface software layers are an essential component for allowing scientists to efficiently access data. They are located between the system software layer (i.e. storage QOS, RDMA networks, container runtime, etc.) and the core software developed by the domain scientist implementing the core of the scientific analysis (see MT-DMA ST1).

The strategy of MT-DMA ST2 is to focus the world-leading activities of the Helmholtz partners onto the development of ready-to-use tool sets that can handle the high-throughput data analysis and simulations for research in *Matter* and other fields. Such tool sets should offer a uniform, task-dependent distribution to the individual hardware layers in a heterogeneous environment in addition to the integration of ecosystem components such as uniform memory management with platform-agnostic data structures or single-source kernel programming.

Providing sustainable software solutions that accompany the experiments over their lifetime is a key component even if computing architectures continue to increase in heterogeneity and diversity. The software solutions to be developed within MT-DMA ST2 will thus enable a broad utilization of upcoming leading-edge computing platforms, including X86 and ARM CPUs, GPUs, and FPGAs. Based on their modular design, these solutions will offer flexibility to deal with experiments or simulations in high-energy physics, photon or neutron science environments, as well as automated or experimenter-in-the-loop scenarios [DMA-7].

MT-DMA ST2 will provide and maintain a variety of sustainable, enabling software solutions for the worldwide scientific communities in collaboration with domain-specific knowledge provided by the Helmholtz researchers (see MT-DMA ST3): Increasing volume, rate, and complexity of data in photon and neutron science will be addressed within MT-DMA ST2 by multiple software development efforts (e.g. XATOM, XMDYN, CrystFEL, OnDA, BornAgain). Novel particle accelerator designs will be supported by state-of-the-art simulation codes (PIConGPU) that will be made exascale-ready (see Cross-Cutting Activity of MT-DMA with the Research Field *Information*).

Solutions from different Helmholtz partners will be integrated, for example ALPAKA with Vc for integrating various programming models for parallelization on hardware ranging from CPUs to GPUs and FPGAs, and ALFA with DD4HEP for geometry description in simulation and reconstruction of particle experiments. This approach is recognized as a promising concept for optimizing synergy between the partners, minimizing maintenance effort, and maximizing the reach of solutions developed by MT-DMA ST2.

With the increasing complexity of data, machine learning (ML) has become an inevitable method for data analyses. The recent observation at the LHC of events where a Higgs boson decays in association with top quarks is one example of a measurement that is only possible with advanced data selection methods based on ML and deep learning. Combined with well-established analysis techniques, ML methods provide a path for *in-situ* data analysis even for highly complex big data [DMA-8] and also a natural collaboration area with the Helmholtz Incubator platforms HAICU and HIP, while picking up existing efforts started within e.g. the Helmholtz Innovation Pool project AMALEA.

MT-DMA ST2 will apply ML methods to a large and diverse field of applications (see MT-DMA ST3), from ultraprecise semantic segmentation methods to methods dedicated to the detection of tiny objects in large volumes or 3D image reconstruction. ML methods will be used for optimizing and controlling machines, for direct knowledge extraction from unreconstructed image and event data, and for improving statistical iterative data reconstruction methods by building fast-forward simulations (surrogate models) [DMA-9]. For this purpose, large amounts of synthetic data need to be generated. Together with the abundance of data from high-energy physics or photon science experiments, these data are the fuel for training ML methods. MT-DMA ST2 will provide federated hard- and software infrastructure for ML within a distributed ML laboratory as initiated within AMALEA.

While all these approaches rely on classical computing hardware, many scientific questions in such diverse fields as high-energy physics, warm dense matter, materials science, and even molecular biology are so complex that they require new computational approaches. Prominent examples are simulations of quantum systems that today challenge even the largest high-performance computers. In some cases, quantum simulations, quantum annealing, and even fully developed quantum computing can help to solve such problems efficiently. MT-DMA ST2 takes a high-risk, high-gain approach by exploring these techniques at a very early stage, evaluating their use for both future data analysis and simulation tasks.

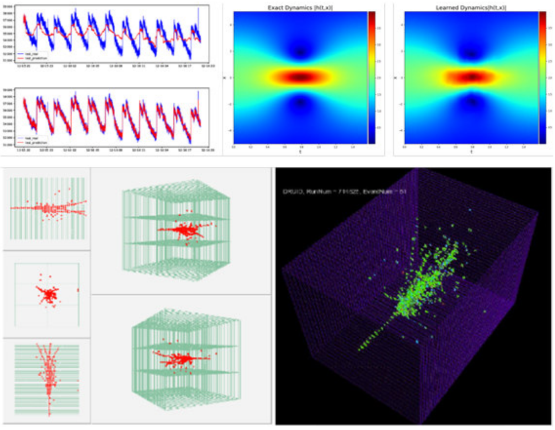


Figure 13: Machine learning for optimizing accelerators (top left), solving the Schrödinger equation (top right, PDE vs. DNN), and simulating particle showers in high-energy physics (bottom) (from DMA-ST2).

ST3 – The Digital Experiment and Machine: MT-DMA ST3 focuses on complex experiments, large-scale instruments, sources, and machines at the research centers in *Matter*, connecting users and facilities and ranging from experiments using photons, neutrons, and ions to experiments in high-energy physics.

MT-DMA ST3 addresses machine optimization hand in hand with feedback from the experiment for both automated and experimenter-in-the-loop rapid feedback. The latter is accompanied by fast, *in-situ*, and *in-transit* solutions for near-real-time analysis of data and online visualization, integrating facility, experiment, and user feedback into the data lifecycle.

Near-real-time analysis is one of the most desired and often needed capabilities for experiments. Both effective real-time analysis and rapid near-real-time offline processing are required to enable clear-cut decisions, e.g. whether to change a sample or the instrument conditions already during a running experiment. Automated, fast, and scalable online knowledge extraction has been identified as one of the most challenging issues for both optimization of experimental conditions and data reduction (see MT-DMA ST1).

MT-DMA ST3 will thus provide experiment-specific methods and algorithms for data extraction and reduction in a modular and portable way [DMA-10], especially fast and scalable ML algorithms (see MT-DMA ST2), real-time high-resolution 3D visualization (ISAAC), and streaming data processing (HiDRA). Software packages covering a wide range of applications across facilities and application areas, such as OnDA in photon science or BornAgain in neutron science, will be improved and expanded in collaboration with domain researchers.

Controls and feedback technologies are key to setting up and operating complex experiments and mid- to large-scale accelerators. The sheer number of sensors dominates future large-scale instruments, where experiments are challenged by the complexity of their detectors and setups. In an initial stage, functional commonalities between accelerator, beamline, and experiment controls will be evaluated, followed by a research phase on scalable software architectures for future control systems. These should enable the exploitation of operation-critical data, i.e. the “health" of an instrument or experiment, and knowledge extraction with respect to performance, availability, and reliability [DMA-11], aiming for predictive analysis and preventive maintenance in order to optimize the reliability and availability of large-scale systems and complex experiments.

At the same time, the increasing rate, volume, and complexity of data requires the development of a new species of user-oriented control interfaces that integrate controls with experimenter-in-the-loop feedback, allowing for interactive optimization of complete experiments, including machines, radiation sources, and detector setups (see MT-DMA ST1). This is particularly the case for user facilities where many users of the control system are non-experts. ML algorithms and methods (see MT-DMA ST2) will become a major ingredient to advance the optimization of large-scale accelerators, as ongoing efforts at the European XFEL (Ocelot), BESSY, PETRA III and ELBE (AMALEA) demonstrate.

Start-to-end simulations – often dubbed digital twins – are becoming essential to effectively plan and analyze experiments using close-to-reality simulations. Digital twins of complete accelerators and radiation sources enable full virtual control and optimization of sources, while virtual experiments can use the input from the machine to compute the expected experimental measurement according to the detector modalities used. In both cases, optimized (surrogate) models (see MT-DMA ST2) can potentially reduce the development, setup, and computation time drastically and allow for fast feedback during experiments and operation.

In MT-DMA ST3, one goal is to develop digital twins of accelerators, radiation sources, and experiments [DMA-12] that allow for fusing the complex measured data with simulated synthetic diagnostic data. This will enable quantitative comparison and subsequent decision-making based on benchmarking, providing for example a better understanding and optimization of operational procedures.

Required analysis capabilities call for models such as Simulation-as-a-Service (SaaS) that combine simulation modules via standardized interfaces and take advantage of surrogate models made possible by deep learning. To allow for open, versatile, reusable, and scalable SaaS, common self-describing, scalable file standards (openPMD, NEXUS) and shared APIs will become a key design issue.

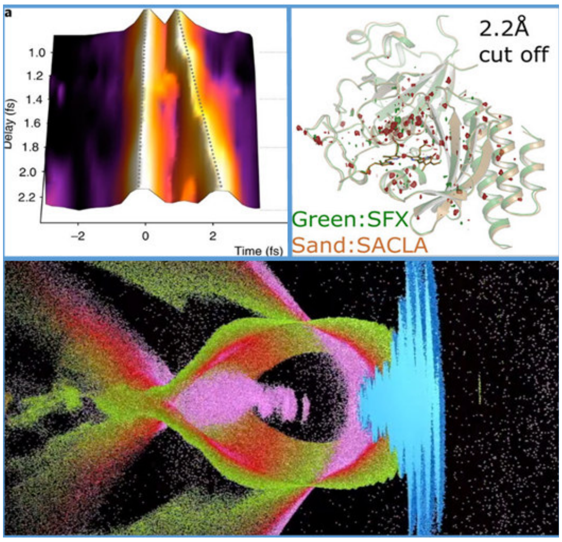


Figure 14: Reconstruction of an attosecond double pulse from an X-ray free-electron laser (top left), reconstruction of the structure of a bacterial photoreceptor using serial femtosecond crystallography (top right), GPU-accelerated simulation of a hybrid laser wakefield/plasma wakefield electron accelerator (bottom) enabled by MT-DMA solutions (from DMA-ST3).

Expected Results

The work program for MT-DMA is structured along milestones, which are shown in Table 3. The first few milestones describe Topic-wide ones, while the remaining ones are specific to individual Subtopics.

Table 3: Milestones of the work program for the Topic MT-DMA

Milestone		Subtopic	Year
DMA-1	Definition of the structure and content of the S4M portal	ST1–3	2023
DMA-2	Launch of the S4M portal	ST1–3	2024
DMA-3	Online availability of all solutions provided by MT-DMA via S4M	ST1–3	2027
DMA-4	Organization of a workshop that defines and strengthens synergies in data lifecycle management among the participating facilities and communities	ST1	2022
DMA-5	Review and gap analysis of existing common tools for implementing a data lifecycle management system in a distributed computing environment that respects FAIR principles	ST1	2024
DMA-6	Review of and documentation of “lessons learned” from the implementation of a generic prototype of a data lifecycle management system in a distributed computing environment that respects FAIR principles	ST1	2027
DMA-7	Provision of a directory of interconnectable software packages including examples to cover the whole simulation and experiment life cycle	ST2	2023
DMA-8	Integration of near-real-time/online data analysis solutions for extreme-scale data into the software toolbox of MT-DMA	ST2	2025

DMA-9	Integration of surrogate models into simulation of multisource, multimodal experiment setups	ST2	2027
DMA-10	Provision of prototypic examples of near-real-time analysis allowing online feedback for experiments based on standardized evaluation workflows	ST3	2024
DMA-11	Provision of an exemplary blueprint for extraction and visualization of operation-critical “health status” data for machines and experiments on an automated basis	ST3	2025
DMA-12	Successful demonstrators of digital twins providing virtual data sets mimicking real-time, real-data operation	ST3	2027

Synergies and Collaboration

As a new Topic in PoF IV, MT-DMA is an integral and unique part of the digitalization strategy of the Helmholtz Association. MT-DMA provides an anchor point for *Matter*-related developments of the Helmholtz Incubator “Information and Data Science” in PoF IV and is complementary to the generic, overarching approach of the newly established Research Field *Information*. MT-DMA relies on generic solutions that are being adapted to the needs of the researchers in *Matter*, while enabling digital solutions developed within *Matter* to be used in other Research Fields and by new scientific communities.

Together with the Research Field *Information*, MT-DMA will establish a long-term Cross-Cutting Activity “Information and Data Management” in PoF IV with two pilot projects, one on enabling exascale-ready plasma simulation and one on applying quantum computing to warm dense matter high-energy, high-energy-density physics (see Volume I, Section 5.1).

MT-DMA is well placed in the European and international community. Existing distributed infrastructures for data lifecycle management, transport, and analysis, including WLCG and Tier-2 facilities, will be complemented by new infrastructures driven at Helmholtz (HDF, FAIR Tier-0, IDAF), national (NFDI), and international (EOSC, ESCAPE) levels, and will be adapted to the specific community needs in collaboration with national and international partners through projects and platforms such as ExPaNDS, PaNOSC, and HIFIS. Centers that integrate data and simulation sciences for understanding complex systems, such as the newly inaugurated Center for Advanced Systems Understanding (CASUS, by HZDR, UFZ, MPI-CBG, and Uniwersytet Wrocławski) or the proposed Center for Data and Computing Sciences (CDCS, by DESY/Universität Hamburg) in Hamburg, are highly relevant to research in MT-DMA. Moreover, on the high-energy physics side, ALFA, FairMQ, and FairRoot are being developed in a collaboration between GSI and CERN to support particle physics experiments with simulation, reconstruction, and analysis.

Tight coupling of the MT-DMA activities with the domain experience of researchers in the *Matter* Programs MU and MML and with MT-ARD and MT-DTS is strongly enforced. With PIConGPU, MT-DMA provides one of the best scaling particle-in-cell codes for plasma physics. Software solutions such as SIMEX_PLATFORM (European XFEL, PaNOSC) or FairROOT provide a blueprint for an open, modular, and interoperable platform for digital twins of experiments, while the software packages HiDRA for fast data transport, OnDA for real-time image analysis, and CrystFEL for serial crystallography have opened up new fields with impact far beyond the Helmholtz Association. They will be developed further and increased in scale in close collaboration with the Research Topic RT3 in MML and European XFEL. Open and self-describing data format standards (NEXUS, openPMD) will enable exchange between data analysis and simulation tools. They are already widely used within photon and neutron science as well as plasma and accelerator physics and are being further developed in collaboration with those scientific communities.

Infrastructures

The developments in MT-DMA ST1 are expected to be implemented and used by the DESY IDAF LK II infrastructure (see Volume III) as well as by the other data centers in the Research Field *Matter*. Additionally, the developments of all the MT-DMA Subtopics together form a software "infrastructure" basis enabling successful research in *Matter*, which will be made available through the S4M portal.

Opportunities and Risks

The development and implementation of a generic, portable, and scalable data lifecycle management system will unite the data analysis approaches within the Research Field *Matter*. Thanks to the strong international involvement of the MT-DMA partners in strategic developments on the national and international level, it will influence developments well beyond the Research Field. As a provider of facilities within *Matter*, we will offer a platform for the harmonization of solutions that is complementary to existing national and international efforts.

In many fields, the efficiency of data acquisition, transfer, handling, and analysis is presently the bottleneck for the processing of large sample series, presenting an opportunity for MT-DMA to have high impact. The challenge will be to support cross-community, modular developments and integration into existing infrastructure, in order to react to diverging efforts between communities. Early adaption of advanced computing technologies including exascale and quantum computing promises future technological benefits and needs to be carefully evaluated. A strong collaboration with the Research Field *Information* is essential to be prepared for future technological changes. It will be pursued in a common Cross-Cutting Activity that will address two upcoming technologies, exascale and quantum computing, as its two pilot projects.

Full-scale digital twins of experiments including machines, radiation sources, and detectors would for the first time push the digital-twin model pioneered in particle, hadron, and nuclear physics to a much greater variety of facilities and user communities than ever before.

One risk is posed by not adequately meeting the challenges of high-data-rate experiments and large data volumes. This would reduce capability and the rate of scientific discovery in fields from MML to MU, especially in diverse fields such as photon and neutron science where users from outside of computing-based domains rely on computing infrastructure and software to be developed for them in order to obtain their results.

Finally, MT-DMA will cover new ground in the evaluation of data and source code citation as a measure to advance the visibility of scientific software and data, including citable data and software repositories in S4M. This is well in line with the rise of data and software repositories as important sources for scientific research. The risk here is that software and data still lack quantitative measures of impact when compared to standard scientific publications, resulting in difficulties when assessing the real impact of MT-DMA.

MT-DMA could only be realized as a new Topic in MT by drawing resources from MT-ARD, MT-DTS, and the other two *Matter* Programs, MU and MML. It thus bears the risk of falling short of reaching its goals due to lack of resources. MT-DMA will mitigate this risk by adapting existing solutions to the needs of *Matter* whenever possible. MT-DMA will create and help to coordinate the synergetic development of digital solutions with the Research Field *Information*, with the Helmholtz Incubator "Information and Data Science", and as part of the digitalization strategy of the Helmholtz Association. MT-DMA will also use its strong connections to national and international projects and programs on digitalization to foster reusable, interoperable, and modular solutions adaptable to research within *Matter*. With this approach, MT-DMA aims at minimizing development and maintenance effort, thus optimizing the use of the resources available in order to focus on the needs of researchers within *Matter*.

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3. PROGRAM ORGANIZATION

3.1. Strategic Partners and Cooperation

The Program MT is closely integrated into networks in Germany and beyond and has been part of much ongoing fruitful collaboration in the PoF III period. MT-ARD, MT-DTS, and MT-DMA are inherently international. Many cooperations and collaborations exist and are being developed between the Helmholtz centers and German and international partners from universities, research labs, and industry.

MT is part of a number of activities that span several Topics, Programs, and/or Research Fields, most notably in the field of information and data management (compare the corresponding Cross-Cutting Activity (CCA) together with the Research Field *Information*, cf. Volume I, Section 5.1), but also, to a smaller extent, in other Research Fields, such as *Health* and *Energy*.

Inherent to all three Topics of the Program MT is the close cooperation with German and international universities, by virtue of the design and focus of the Topics. The centers within MT collaborate intensively with many university partners on multiple research projects. In many cases, strategic partnerships with the nearby universities are the cornerstone of focal points of local research. Several centers are involved in **clusters of excellence** and **collaborative research centers** (CRCs/SFBs) together with selected university partners, such as the clusters of excellence Physics of Life (TU Dresden with HZDR as partner) and Quantum Universe (U Hamburg with DESY as partner). The most important strategic university partners of the Program MT are listed in Table 4. The strategic university partners are of vital importance to the Program. Only the most relevant ones could be listed here, cooperations exist with many more. With many university partners, there are **joint W2/W3 professor appointments** (more than 20 within the Program, together with local, national, and international universities) and programs such as **joint graduate schools** for the promotion of doctoral students and young researchers.

Table 4: Selected strategic university partners of MT

Partner	Topic	Activities
Friedrich-Schiller-Universität Jena	MT-ARD, MT-DTS	Helmholtz Institute Jena, joint research groups/activities, cluster of excellence Balance of the Microverse; HGS-HIRe graduate school, Research School of Advanced Photon Science
Johann Wolfgang Goethe-Universität Frankfurt am Main	MT-ARD, MT-DMA	Joint research activities related to GSI/FAIR; joint use of existing infrastructures; HGS-HIRe graduate school
Heinrich-Heine-Universität Düsseldorf	MT-ARD	Cooperation for JuSPARC/ATHENA
Helmut-Schmidt-Universität Hamburg	MT-DMA	DASHH graduate school
Humboldt-Universität zu Berlin	MT-ARD, MT-DTS	Accelerator development, high-brilliance beams, and detector development
Johannes Gutenberg-Universität Mainz	MT-ARD	Joint research activities related to GSI/FAIR; joint use of existing infrastructures; cluster of excellence PRISMA+; RTG AccelencE
Rheinisch-Westfälische Technische Hochschule Aachen	MT-ARD	Cooperation for JuSPARC/ATHENA
Technische Universität Darmstadt	MT-ARD	Joint research activities related to GSI/FAIR; joint use of existing infrastructures; HGS-HIRe graduate school; RTG AccelencE
Technische Universität Dresden	MT-ARD, MT-DMA	Cluster of excellence "Physics of Life", DRESDEN-concept, OncoRay – National Center for Radiation Research in Oncology, accelerator applications, cancer therapy, big data, high-performance computing, AI, ML, GPU/FPGA computing
Technische Universität Hamburg-Harburg	MT-DMA	DASHH graduate school, advanced materials
University of Crete	MT-ARD	Cooperation for JuSPARC/ATHENA
Universität Hamburg	MT-ARD, MT-DTS, MT-DMA	Accelerator development, in particular plasma acceleration; detector development, in particular for the LHC; graduate schools; clusters of excellence; planned CDCS center
Universität Heidelberg	MT-DTS	Joint research activities related to superconducting sensors; HGS-HIRe Graduate School

The Program MT focuses on the development of fundamental technologies and does not primarily serve the immediate needs of single research groups or facilities. However, MT places special importance on the collaboration with major national and international accelerator centers, such as CERN, SLAC, ESS, or European XFEL. Many technologies researched and developed within MT have direct applications at such laboratories with respect to particle acceleration, detector systems and the data handling of the respective experiments. Other important partners range from the German national metrology laboratory PTB to industrial partners such as Bilfinger Noell.

In general, the number of non-university partners of relevance to our Program is high. Several non-university partners, primarily in Germany, are of key importance for the Program to the extent that they contribute centrally to the definition and success of the Program MT. These strategic partners are listed in Table 5.

Table 5: Selected strategic non-university partners of MT

Partner	Topic	Activities
Bilfinger Noell	MT-ARD	Superconducting undulators
CERN, Switzerland	MT-ARD, MT-DTS, MT-DMA	Accelerator science and technology, superconductivity, detector development, high data rates
European Spallation Source (ESS), Sweden	MT-DMA	Collaboration on software projects, e.g. EU project SINE2020
European XFEL	MT-DTS, MT-ARD, MT-DMA	HIBEF beamline, DASHH graduate school, accelerator development, fast imaging detectors, high-power laser systems, start-to-end simulations, fast image reconstruction
Institute Laue-Langevin (ILL), France	MT-DMA	Collaboration on software projects, e.g. EU project SINE2020
ITEP Moscow, Russia	MT-ARD	JuSPARC/ATHENA
Jefferson Laboratory, USA	MT-ARD	Collaboration on SRF technology, HOM-damped cavities
Max Born Institute Berlin (MBI)	MT-ARD	Collaboration on photocathode laser
Physikalisch Technische Bundesanstalt (PTB)	MT-ARD	PTB's Metrology Light Source (operated by HZB) for accelerator studies and research
SIOM Shanghai, China	MT-ARD	JuSPARC/ATHENA
SLAC/LCLS, USA	MT-ARD	Accelerator technology development, THz technologies, development of advanced accelerator technologies, high-power laser systems, HED simulations
Weizmann Institute of Science/WHELMI, Israel	MT-ARD	Development of advanced accelerator technologies, high-power laser systems, laser target development, plasma acceleration simulations

3.2. Infrastructures

The first-class Helmholtz LK I and LK II infrastructures of the Research Field *Matter* are essential for the success of our Program. Tables 6 and 7 list the existing/approved (e.g. currently under construction) and planned infrastructures directly related to the Program MT, respectively. The planned infrastructures are differentiated according to whether the contribution of the centers is smaller (Table 7a) or larger (Table 7b) than 15 million euros. The former may be handled within a center's budget, whereas the larger projects require the approval of the Helmholtz General Assembly.

Table 6: Existing and approved large-scale research infrastructures (> 2,5 Mio. EUR)

Name	Contributing Centers	Start of Operation	Description
ATHENA	HZB, HZDR, DESY, FZJ, GSI, HI Jena, KIT	2022	Distributed infrastructure for plasma acceleration
bERLinPro	HZB	2021	Test facility for high-brightness CW beams and energy recovery in SC accelerators
BESSY II[3]	HZB	1998	Third-generation soft X-ray user facility (MML) utilized for accelerator R&D, LK II facility
Cryoplatform	DESY	2020	Cryogenic infrastructure for experiments and detector development
cStart	KIT	2026	Compact storage ring for accelerator research and technology
DAF[3]	DESY	2020	Detector assembly facility for high-precision silicon detectors
ELBE @ ELBE Center	HZDR	2004	Multiple radiation source powered by superconducting (SC) CW electron LINAC, LK II facility
FLASH[3]	DESY	2005	XUV and soft X-ray free-electron laser, 10% of beam time dedicated to accelerator R&D, LK II facility
FLUTE	KIT	2021	Test facility for generation of intense sub-picosecond electromagnetic pulses
HDF[3]	DESY, KIT, GSI, FZJ, AWI, and DKFZ	2019	Helmholtz Data Federation
High Power Laser System	GSI	2008	PW-class laser PHELIX with dedicated plasma accelerator infrastructure and metrology
High Power Laser Systems[3]	HI Jena	2010/2015	High-power laser systems (JETI200 and POLARIS) with dedicated plasma accelerator infrastructure and metrology
HL-LHC[3]	DESY, KIT	2026	High-luminosity large hadron collider at CERN
HSS	KIT	2022	Laboratory for the production and test of superconducting sensors
KARA[3]	KIT	2000	Electron storage ring as platform for accelerator and detector research (formerly ANKA storage ring)
Petawatt Lasers @ ELBE Center	HZDR	2008	High-power laser systems with dedicated plasma accelerator infrastructure and metrology
SINBAD	DESY	2019	Accelerator research facility with different experiments
Supralab	HZB	2017	Application laboratory for developing CW SC accelerator technology
Testbeam	DESY	Early 1980s	Electron test beam facility at the DESY II synchrotron for detector development
Tier-2/IDAF[3]	DESY	2005	Interdisciplinary Data and Analysis Facility for *Matter* Research, LK II facility
X-Ray Detector Program	DESY	2016	Infrastructure for development of specialized pixel detectors for hard and soft X-rays

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3 This research infrastructure has relevant contributions also in other programs of the Research Field Matter and will therefore also be listed there.

In the following two tables, the status of the projects in indicated by the following states:

- In discussion (disc.)
- Preparation: creating the TDR/feasibility study (prep.)
- Proposal submitted (prop.)
- Funding commitment: > 50% of the estimated project costs (fund.)

Table 7a: Planned large-scale research infrastructures (2,5 - 15 Mio. EUR)

Name	Contributing Centers	Helmholtz Investment (Total Project) in TEUR	Planned Start of Operation	Project Status	Description
PETRA III/IV Detectors	DESY	3.500 (3.500)	2021	disc.	Infrastructure for PETRA detectors
KALDERA	DESY	2.000 (2.000) (phase 1)	2020	fund.	Platform for advanced laser systems; phase 2 with additional funding will reach into PoF V

Table 7b: Planned large-scale research infrastructures (> 15 Mio. EUR)

Name	Contributing Centers	Helmholtz Investment (Total Project) in TEUR	Planned Start of Operation	Project Status	Description
DALI[4]	HZDR	tbd (180.000)	2030	prep.	Dresden Advanced Light Infrastructure, conception of a follow-up of the ELBE facility (pulsed IR to THz source, VUV option under discussion)
DDL	DESY, GSI, HI Jena, KIT	31.600 (31.600)	2023	prop.	Distributed Detector Laboratory
InnoMatSy[4]	HZG	tbd	2026	prep.	*In-situ* innovation platform for multifunctional material systems; financial scope and participating centers currently being planned.

3.3. Management

The management structure of the Program MT was established with the start of the PoF III period. The Program is represented by two spokespersons. They chair the management board of the Program, in which two spokespersons of each Topic and the spokespersons of the associated LK II facility are permanent members. The MT management board meets regularly to discuss progress in the Program as well as issues and problems as they are arising.

Program-wide decisions related to the normal Program execution are taken by the management board, usually by consensus. The management board is also an important component of the information flow: Information from the

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[4] This research infrastructure has relevant contributions also in other programs of the Research Field Matter and will therefore also be listed there.

management of the Research Field *Matter* is usually distributed to the spokespersons of the Programs and then via the management board to the Program participants in the different Topics. Each Topic within MT also has an internal management structure, including the Topic spokespersons and Subtopic spokespersons.

A key role of the management board is the development and continuous further development of a strategy for MT. The development of common initiatives and actions that go beyond a single Topic is another focus. Progress within the Topics is carefully tracked, including monitoring of the milestones at the Topic level.

The management board is supervised by the MT executive board, in which all participating centers are represented. Members of the MT management are permanent guests in the executive board. The executive board meets at least once a year, typically during the annual Program meeting, and discusses the general direction of the Program.

3.3.1. Talent Management

The recruitment and development of talent are of utmost importance for the success of the Program MT. Ensuring that the right people are given optimal conditions and opportunities is a key to success.

Each of the centers participating in MT has developed center-oriented talent development plans, recognizing that most of the talent management and development is organized and decided at the centers. Students and graduated researchers are embedded in graduate schools and have access to a broad range of scientific, technical, and career-related training and mentoring courses. The Program MT can complement these efforts by a number of specific actions.

A key aspect continues to be that, for a technically oriented Program like MT, both top-level scientists and top-level engineers need to be recruited. Both groups present slightly different challenges. Regarding the scientists, the creation of MT is an important step within an overall strategy to increase the scientific standing and visibility of this technical work. Moving away from the still rather common view that technical tasks are purely service tasks, without their own scientific benefit and justification, is our explicit goal and one reason for the creation of MT. Regarding engineers and related people, in addition, developing attractive programs and environments together with attractive career perspectives that allow for greater freedom than commonly accessible to engineers in the field can be a key ingredient in competing more effectively with industry for top people. In return, the same arguments and the same access to state-of-the-art infrastructure and interesting projects make our people more interesting to other employers within and outside of science.

The Program will also help to create an interesting and attractive environment. As part of the annual calendar of events, MT organizes a yearly Program meeting. A strong focus of this meeting is to give young researchers and engineers a platform where they can present their work and their results. In addition to the traditional talks during topical sessions, we have instituted a well-attended poster session during this meeting, with typically close to 100 posters presented. This poster session is complemented by a speed talk session in which a number of poster presenters are given the opportunity to present their poster in a short, 5 min presentation to the full audience of the meeting. Another element of training and supporting young members of the Program are the MT student days, which take place on the days before the annual meeting. During this event, students and young postdocs associated with the Program are given the opportunity to organize their own meeting, on both scientific and non-scientific issues. Career planning topics are typically one important aspect of these meetings, in addition to networking and exchanging information among the participants. Continuous training and development of our engineers and technical personnel are a key part of our talent management strategy for enabling the realization of our technically challenging projects.

In PoF III, we organized a number of additional events especially directed at young researchers. For example, we ran two week-long schools concentrating on aspects of detector development (Heraeus seminars). We offered regular hands-on training events, e.g. for microTCA and related hardware. Moreover, we will actively encourage young researchers to spend time at centers contributing to MT, for example when working on system integration, commissioning, or test beam activities, to widen their professional experience and build networks.

3.3.2. Transfer of Knowledge and Technology

Making our developments available to a broader public outside the Research Field *Matter* is an important element of the strategy of the Helmholtz Association and of the Research Field. Transfer in this context can mean the transfer to other research groups or fields, or the transfer to industry and society at large.

Transfer of knowledge and technology in MT thus contains joint technology developments and commercialization, promotion of spin-off companies, knowledge transfer by minds, joint supervision of doctoral students with industry, participation in international and multi-disciplinary collaborations and consortia.

In general, the knowledge and technology transfer process in the Helmholtz Association is managed through dedicated departments at the participating centers. They provide the required professional support and help. MT is supporting these activities by developing a Program-wide policy on IP ownership and sharing in agreement with the participating centers. As a Program with many participants, MT fosters interdisciplinary collaborations and encourages the installation of technological standards and common, transferable solutions. Breakthrough technology is thus designed from the start with the use at other facilities or experiments in mind. The development philosophy moves away from the highly targeted “single-application” solutions towards systems. These can be industrialized more conveniently, profitably, and sustainably, there being a larger market. This strategy already reaches out beyond MT to other European partners. One example for such developments is the microTCA industrial standard driven by MT-ARD, as supported by the Helmholtz Validation Fund and developed in close cooperation with industry, which is now broadly used. Another specific example is an ultra-fast camera system developed jointly within MT-ARD and MT-DTS to monitor particle beams, which is now used in a growing number of accelerator facilities. Licensing negotiations with an industrial partner are in progress. Other examples are cases, where technologies have been marketed through spin-off companies. Recent new companies are X-Spectrum for large-area hybrid pixel detectors or Class 5 Photonics for brilliant laser systems.

For PoF IV, MT is proposing a number of more Program-specific measures to enhance transfer and foster industrial relations. We explore the possibility to organize industrial road-shows at our annual meetings. These could be combined with our technology scouting activities and a networking forum to initiate MT-industry consortia. The measures will also serve to foster the exchange with MT-alumni (“transfer by minds”), now working in industry. MT envisages to kick-start *Matter* career fairs as a way to offer industry access to highly-educated young talents.

MT has a strong tradition of working closely with industry. For example, researchers from MT-ARD and Bilfinger Noell jointly developed the first commercially available superconducting undulators. The progress in superconducting RF technology, a key expertise in the Helmholtz Association, is an excellent illustration of a most successful, long-term collaboration with industry: Many critical system components have long been fabricated by industry, with MT scientists and engineers closely following the production. Problem-solving-oriented communication with Helmholtz experts is essential for success, and has been a key to the technology transfer established so far. As a result, vendors now feel confident to guarantee the performance of complete systems. The cooperative approach will be expanded to develop industry-supplied turn-key SRF systems. This relies heavily on the availability of Helmholtz infrastructures for SRF testing throughout all production stages. The full suite of infrastructures for developing new CW SRF accelerator systems, for example, starting from the testing of new materials to full accelerator modules, is available with SupraLAB@HZB, which will be available to users from both science and industry. These aspects of MT are already helping to develop compact SRF accelerators for industry and society, such as facilities for the production of medical isotopes, MESA at HIM, TARLA in Turkey, and POLFEL in Poland. In the same way the proposed DDL will, if funded, give access to cutting edge development and characterization facilities for detectors to users from science and industry.

Societal benefits are anticipated from the development of technologies for medical applications. An example is the development of a dedicated 70 MeV cyclotron for the treatment of intraocular tumors (High Quality Proton Cyclotron for Eye Treatment) foreseen in MT-ARD, 3D-ultrasound computer tomography (3D-USCT) is a world-leading technology developed by MT-DTS researchers for early breast cancer diagnosis. Real-time imaging techniques as well as novel sensor concepts and data handling methods studied in the MT research program are also highly relevant for medical applications.

MT researchers initiate and contribute to large-scale EU projects and multilateral collaborations with international partners from academia and industry. We provide critical expertise for the definition of national and international roadmaps of large-scale facilities or technologies. We drive and support the activities of national science committees (e.g., KfB, KET, KAT, KHuK) and organizations, thus providing essential input to the political decision makers.

With the outlined specific measures and the MT knowledge and technology transfer concept, MT is poised to efficiently share *Matter*-driven technologies with the wider society.

4. RESOURCES

The following tables show the costs of the Program MT by Topic and the expected distribution of personnel resources for activities in FTE.[5]

Please note the used notation which applies to the entire proposal: Costs are given in thousand euros (TEUR), and for all resources numbers the thousands separator is a dot, and the decimal separator is a comma.

Table 8: Costs and personnel resources of the Program MT and its Topics, planned for 2021. The costs include general and administrative costs, internal services etc.

Program costs (TEUR)	**80.971**
Accelerator Research and Development	60.191
Detector Technologies and Systems	12.448
Data Management and Analysis	8.332
Program personnel (FTE)	**424**
Accelerator Research and Development	**264**
Scientists	139
Doctoral students	39
Scientific support personnel	86
Detector Technologies and Systems	**93**
Scientists	54
Doctoral students	13
Scientific support personnel	26
Data Management and Analysis	**67**
Scientists	50
Doctoral students	14
Scientific support personnel	3

Table 9: Program resources by center (in TEUR), planned for 2021. The costs include general and administrative costs, internal services etc.

Proposed program costs	**80.971**
DESY part costs	**24.896**
thereof personnel costs (including personnel of infrastructure)	15.303
FZJ part costs	**1.445**
thereof personnel costs (including personnel of infrastructure)	946

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[5] The resources listed under GSI include the Helmholtz institutes in Jena and Mainz. The IKP contributions in the framework of TransFAIR are listed separately.

TransFAIR (FZJ/GSI)* part costs	**1.029**
thereof personnel costs	450
GSI part costs	**8.409**
thereof personnel costs (including personnel of infrastructure)	5.523
HZB part costs	**13.666**
thereof personnel costs (including personnel of infrastructure)	8.237
HZDR part costs	**11.399**
thereof personnel costs (including personnel of infrastructure)	6.143
HZG part costs	**403**
thereof personnel costs (including personnel of infrastructure)	327
KIT part costs	**19.725**
thereof personnel costs (including personnel of infrastructure)	8.954
DESY part investments	
continuing investments	2.436
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	2.453
FZJ part investments	
continuing investments	68
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
TransFAIR (FZJ/GSI) part investments	
continuing investments	0
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
GSI part investments	
continuing investments	1.615
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
HZB part investments	
continuing investments	2.155
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	2.093
HZDR part investments	
continuing investments	1.092
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	1.467
HZG part investments	
continuing investments	69
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
KIT part investments	
continuing investments	1.553
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	3.769

**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.*

Table 10: Reconciliation of total program costs to cash expenditures (in TEUR). Noncash expenditures include depreciation, reserves, variations in receivables and liabilities.

DESY program costs	24.896
- noncash expenditures	3.850
+ continuing investments	2.436
+ ongoing individual large investments > € 2,5 million	2.453
DESY cash expenditures	**25.935**
FZJ program costs	1.445
- noncash expenditures	73
+ continuing investments	68
+ ongoing individual large investments > € 2,5 million	0
FZJ cash expenditures	**1.440**
TransFAIR (FZJ/GSI)* program costs	1.029
- noncash expenditures	0
+ continuing investments	0
+ ongoing individual large investments > € 2,5 million	0
TransFAIR (FZJ/GSI)* cash expenditures	**1.029**
GSI program costs	8.409
- noncash expenditures	1.623
+ continuing investments	1.615
+ ongoing individual large investments > € 2,5 million	0
GSI cash expenditures	**8.400**
HZB program costs	13.666
- noncash expenditures	4.951
+ continuing investments	2.155
+ ongoing individual large investments > € 2,5 million	2.093
HZB cash expenditures	**12.963**
HZDR program costs	11.399
- noncash expenditures	4.782
+ continuing investments	1.092
+ ongoing individual large investments > € 2,5 million	1.467
HZDR cash expenditures	**9.176**
HZG program costs	403
- noncash expenditures	98
+ continuing investments	69
+ ongoing individual large investments > € 2,5 million	0
HZG cash expenditures	**374**
KIT program costs	19.725
- noncash expenditures	3.982
+ continuing investments	1.553
+ ongoing individual large investments > € 2,5 million	3.769
KIT cash expenditures	**21.065**

** Special regulation: The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.*

Table 11: Program personnel capacity by center (FTE), planned for 2021.

DESY part personnel	**154**
Scientists	79
Doctoral students	28
Scientific support personnel	47
FZJ part personnel	**8**
Scientists	8
Doctoral students	0
Scientific support personnel	0
TransFAIR (FZJ/GSI) part personnel	**6**
Scientists	3
Doctoral students	1
Scientific support personnel	2
GSI part personnel*	**75**
Scientists	48
Doctoral students	18
Scientific support personnel	9
HZB part personnel	**55**
Scientists	32
Doctoral students	4
Scientific support personnel	19
HZDR part personnel	**42**
Scientists	26
Doctoral students	8
Scientific support personnel	8
HZG part personnel	**2**
Scientists	2
Doctoral students	0
Scientific support personnel	0
KIT part personnel	**82**
Scientists	46
Doctoral students	7
Scientific support personnel	29

**A large fraction of doctoral students financed from GSI in this Program are employed at a partner university through a Strategic Partnership Program between GSI and the university. Therefore those personnel costs are not included in the costs given here, however, those doctoral students are included in the head count as they will work for the respective Program.*

Current resources

The current personnel resources are listed in the proposed PoF IV structure and are thus not directly comparable to the Program resources for PoF III.

Table 12: Current personnel resources projected to the PoF IV structure, preliminary resources for 2019.

	Helmholtz program		third-party funding	
	TEUR	FTE	TEUR	FTE
DESY	**10.643**	**135**	**1.778**	**26**
Scientists	6.513	69	1.492	18
Doctoral students	673	19	256	7
Scientific support personnel	3.457	47	30	1
FZJ	**724**	**8**	**0**	**0**
Scientists	724	8	0	0
Doctoral students	0	0	0	0
Scientific support personnel	0	0	0	0
TransFAIR (FZJ/GSI)*	**441**	**6**	**0**	**0**
Scientists	271	3	0	0
Doctoral students	43	1	0	0
Scientific support personnel	127	2	0	0
GSI**	**4.556**	**75**	**1.334**	**28**
Scientists	3.623	48	750	10
Doctoral students	528	18	561	17
Scientific support personnel	405	9	23	1
HZB	**4.029**	**55**	**78**	**2**
Scientists	2.508	32	0	0
Doctoral students	156	4	78	2
Scientific support personnel	1.365	19	0	0
HZDR	**2.648**	**41**	**919**	**16**
Scientists	1.871	25	692	10
Doctoral students	303	8	227	6
Scientific support personnel	474	8	0	0
HZG	**251**	**2**	**0**	**0**
Scientists	251	2	0	0
Doctoral students	0	0	0	0
Scientific support personnel	0	0	0	0
KIT	**6.933**	**86**	**892**	**14**
Scientists	4.280	46	618	9
Doctoral students	506	11	91	2
Scientific support personnel	2.147	29	184	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.*

** *A large fraction of doctoral students financed from GSI in this Program are employed at a partner university through a Strategic Partnership Program between GSI and the university. Therefore those personnel costs are not included in the costs given here, however, those doctoral students are included in the head count as they will work for the respective Program.*

5. LIST OF PUBLICATIONS RELATED TO THE PROGRAM PROPOSAL

The following publications have been referenced in the text:

References MT-ARD

[1] Keckert, S. et al., Critical fields of Nb_3Sn prepared for superconducting cavities, Superconductor Science and Technology (2019), doi: 10.1088/1361-6668/ab119e

[2] Köszegi, J. and Knobloch, J., Advanced study of the thermoelectrically generated magnetic field in a nine-cell cavity during the superconducting phase transition, Phys. Rev. AB 22, 052001 (2019). doi: 10.1103/PhysRevAccelBeams.22.052001

[3] Wenskat, M., Optical surface properties and their RF limitations of European XFEL cavities, Superconductor Science and Technology 30(10), 105007 (2017) doi: 10.1088/1361-6668/aa828b

[4] Vennekate, H. et al., Emiittance compensation schemes for a superconducting rf injector, Phys. Rev. Accel. Beams 21, 093403 (2018). doi: 10.1103/PhysRevAccelBeams.21.093403

[5] Barth, W. et al., First heavy Ion Beam Test with a superconducting multi gap CH-cavity, Phys. Rev. Accel. Beams 21, 020102 (2018). doi: 10.1103/PhysRevAccelBeams.21.020102

[6] Wagner, T. Beam-based alignment tests at the Cooler Synchrotron (COSY), proceedings of the 7th Symposium on Symmetries in Subatomic Physics (SSP 2018), Aachen (Germany), June 11-15, 2018. doi: 2018/Journal.999.12345

[7] Studie zur Integration von Kryopumpen in die Vakuumkammern des SIS18 inkl. Kühlsystem, ILK Dresden, ILK-B-1-17-380a; doi: 2018/Journal.999.12345

[8] Winter, D. et al., Laser Cooling of Relativistic Heavy-Ion Beams for FAIR, Phys. Scr. 2015 014048 (2015). doi: 10.1088/0031-8949/2015/T166/014048

[9] Fischer, E. et al., Superconducting Magnets for FAIR", Proc. of IPAC (2017, Copenhagen, Denmark. doi: 10.18429/JACoW-IPAC2017-WEOCB2

[10] Hagenmeyer, V. et al., Information and Communication Technology in Energy Lab 2.0: Smart Energies System Simulation and Control Center with an Open-Street-Map-Based Power Flow Simulation Example, Energy Technology, 4: 145-162. doi: 10.1002/ente.201500304

[11] Arion, T. et al., Transverse resonance island buckets for synchrotron-radiation based electron time-of-flight spectroscopy, Review of Scientific Instruments 89, 103114 (2018). doi: 10.1063/1.5046923

[12] Azima, A. et al., Control of FEL radiation properties by tailoring the seed pulses. New J. Phys. 20, 013010 (2018). doi: 2018/Journal.999.12345

[13] Steinmann, J.L. et al., Continuous bunch-by-bunch spectroscopic investigation of the microbunching instability. Phys. Rev. Accel. Beams 21, 110705 (2018). doi: 2018/Journal.999.12345

[14] Chen, M., et al., Towards femtosecond-level intrinsic laser synchronization at fourth generation light sources. Optics Letters, 43, 2213 (2018). doi: 2018/Journal.999.12345

[15] Schönfeldt, P. et al., Parallelized Vlasov-Fokker-Planck solver for desktop personal computers. Phys. Rev. Accel. Beams 20, 030704 (2017). doi: 10.1103/PhysRevAccelBeams.20.030704

[16] Funkner, S. et al., High throughput data streaming of individual longitudinal electron bunch profiles. Phys. Rev. Accel. Beams 22, 022801 (2019). doi: 10.1103/PhysRevAccelBeams.22.022801

[17] Xin, M. et al., Ultra-precise timing and synchronization for large-scale scientific instruments, Optica 5, 1564-1578 (2018). doi: 10.1364/OPTICA.5.001564

[18] Downer, M. et al., Diagnostics for plasma-based electron accelerators, Rev. Mod. Phys. 90, 035002 (2018). doi: 10.1103/RevModPhys.90.035002

[19] Hilz, P. et al., Isolated proton bunch acceleration by a petawatt laser pulse. Nature Communications 9, 423 (2018). doi: 2018/Journal.999.12345

[20] Couperus, J. et al., Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator, Nature Communications 8, 487 (2017). doi:10.1038/s41467-017-00592-7

[21] D'Arcy, R. et al., Tunable Plasma-Based Energy Dechirper. Phys. Rev. Lett. 122, 034801 (2019). doi: 2018/Journal.999.12345

[22] Loisch, G. et al., Observation of High Transformer Ratio Plasma Wakefield Acceleration. Phys. Rev. Lett. 121, 064801 (2018). doi: 2018/Journal.999.12345

[23] Obst-Huebl, L. et al., All-optical structuring of laser-driven proton beam profiles. Nature Communications 9, 5292 (2018). doi: 10.1038/s41467-018-07756-z

References MT-DTS

[24] Schwandt, J. et al., Design and First Tests of a Radiation-Hard Pixel Sensor for the European X-Ray Free-Electron Laser, IEEE TNS 61,4 (2014). doi: 10.1109/TNS.2014.2304239

[25] Adam, W. et al., P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC. JINST 12, P06018 (2017). doi:10.1088/1748-0221/12/06/P06018

[26] Pennicard, D., et al., LAMBDA 2M GaAs-A multi-megapixel hard X-ray detector for synchrotrons, JINST 13, C01026 (2018). doi: 10.1088/1748-0221/13/01/C01026

[27] Peric, I. et al., A high-voltage pixel sensor for the ATLAS upgrade, NIMA 924, 99-10321 (2019). doi: 10.1016/j.nima.2018.06.060

[28] Allahgholi, A., et al., Front end ASIC for AGIPD, a high dynamic range fast detector for the European XFEL,JINST 11, C01057 (2016). doi: 10.1088/1748-0221/11/01/C01057

[29] Blanco, R. et al., Integrated readout electronics for Belle II pixel detector, JINST 13, 3, C03001 (2018). doi: 10.1088/1748-0221/13/03/C03001

[30] Knittel, G. and Traxler M., EraΣer: A Compact FPGA-TDC Design, IEEE ...

[31] Rota, L., et al., KALYPSO: Linear array detector for high-repetition rate and real-time beam diagnostics. NIMA (2018). doi: 10.1016/j.nima.2018.10.093

[32] Kaever, P. et al., The Common Data Acquisition Platform in the Helmholtz Association. JINST 12, C04004 (2017). doi: 10.1088/1748-0221/12/04/C04004

[33] Mohr, H., et al., Evaluation of GPUs as a level-1 track trigger for the High-Luminosity LHC, JINST/12, C04019 (2017). doi: 10.1088/1748-0221/12/04/C04019

[34] Caselle, M. et al., KAPTURE-2. A picosecond sampling system for individual THz pulses with high repetition rate, JINST 12.01, C01040 (2017). doi: 0.1088/1748-0221/12/01/C01040

[35] Chilingaryan, S. et al., Balancing Load of GPU Subsystems to Accelerate Image Reconstruction in Parallel Beam Tomography. 2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD) (2019). doi: 10.1109/CAHPC.2018.8645862

[36] Karnick, D. et al., Optical links for detector instrumentation: on-detector multi-wavelength silicon photonic transmitters. JINST/12, C03078 (2017). doi: 10.1088/1748-0221/12/03/C03078

[37] Microwave SQUID Multiplexing of Metallic Magnetic Calorimeters: Status of Multiplexer Performance and Room-Temperature Readout Electronics Development. J Low Temp Phys/193, 462 (2018). doi: 10.1007/s10909-018-1878-3

[38] Zakosarenko, V. et al., Coreless SQUID-based cryogenic current comparator for non-destructive intensity diagnostics of charged particle beams, Supercond. Sci. Technol. 32 (2019), 014002, doi: 10.1088/1361-6668/aaf206

[39] Flaschel, N. et al., Thermal and hydrodynamic studies for micro-channel cooling for large area silicon sensors in high energy physics experiments. NIMA 863, 26-34 (2017). doi: 10.1016/j.nima.2017.05.003

[40] Blank, T. et al., High density flex-cable and interconnection technologies for large silicon detector modules. 2018 International Conference on Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC) (2018). doi: 10.23919/ICEP.2018.8374306

[41] Allahgholi, A., et al., AGIPD - "The Adaptive Gain Integrating Pixel Detector at the European XFEL", Journal of Synchrotron Radiation, 26 (1), pp74-82 (2019). doi: 10.1107/S1600577518016077.

[42] Donato, M. et.al., First functionality tests of a 64 x 64 pixel DSSC sensor module connected to the complete ladder readout, JINST 12 (2017) no.03, C03025. doi: 10.1088/1748-0221/12/03/C03025

[43] Kraft-Bermuth, S. et al., Microcalorimeters for X-Ray Spectroscopy of Highly Charged Ions at Storage Rings, Atoms 6 (2018). doi:10.3390/atoms6040059

[44] Sefkow, F. et.al., A highly granular SiPM on tile calorimeter prototype, CALICE collaboration, J.Phys.Conf.Ser. 1162 (2019) no.1, 012012. doi: 10.1088/1742-6596/1162/1/012012

References MT-DMA

[45] https://indico.cern.ch/event/754731/contributions/3127499/attachments/1802108/2939715/LHCC-Status-260219.pdf

[46] Millar, A., et al., dCache, Sync-and-Share for Big Data. Journal of Physics: Conf. Ser. 664, 042038 (2015). doi: 10.1088/1742-6596/664/4/042038.

[47] Jung, C., et al., Optimization of data life cycles, Journal of Physics: Conf. Ser. 513, 032047 (2014). doi: 10.1088/1742-6596/513/3/032047

[48] Schwarz, K., et al., Grid Computing at GSI for ALICE and FAIR -present and future, Journal of Physics: Conf. Ser. 396 032097 (2012). doi :10.1088/1742-6596/396/3/032097

[49] https://www.rd-alliance.org/groups/rda-germany

[50] https://www.openacc.org/about

[51] http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2013/n3759.html

[52] Yoon C.H., et al., Climbing the Data Mountain: Processing of SFX Data. In: Boutet S., Fromme P., Hunter M. (eds) X-ray Free Electron Lasers. Springer, Cham (2018), doi: 10.1007/978-3-030-00551-1_7

[53] Mariani, V., et al., OnDA: online data analysis and feedback for serial X-ray imaging, Journal of Applied Crystallographie, 49(3), 1073 (2016). doi: 10.1107/S1600576716007469

[54] Fortmann-Grote, C., et al., SIMEX : Simulation of Experiments at Advanced Laser Light Sources, NOBUGS 2016 Proceedings - New Opportunities for Better User Group Software 29-34 Oct. (2016). doi: 10.17199/NOBUGS2016.21

[55] Cabanelas, P. et al, EnsarRoot: The framework for simulation and data analysis for ENSAR, Journal of Physics: Conf. Ser. 1024, 012038 (2018). doi :10.1088/1742-6596/1024/1/012038

[56] Al-Turany, et al., ALFA: The new ALICE-FAIR software framework, Journal of Physics: Conf. Ser. 664, 072001 (2015). doi: 10.1088/1742-6596/664/7/072001

[57] Matthes, A., et al., Tuning and Optimization for a Variety of Many-Core Architectures Without Changing a Single Line of Implementation Code Using the Alpaka Library, High Performance Computing 10524, 496 (2017). doi: 10.1007/978-3-319-67630-2_36

[58] Al-Turany, et al., The FairRoot framework, Journal of Physics: Conf. Ser. 396, 022001 (2012). doi:10.1088/1742-6596/396/2/022001

[59] Sailer, A., et al., DD4Hep Based Event Reconstruction, Journal of Physics: Conf. Ser. 898, 042017 (2017). doi: 10.1088/1742-6596/898/4/042017.

[60] https://www.openpmd.org

[61] Burle, J., et al., BornAgain - Software for simulating and fitting X-ray and neutron small-angle scattering at grazing incidence, http://www.bornagainproject.org

[62] Lutz, M. F. M., et al, On the convergence of the chiral expansion for the baryon ground-state masses, Nucl.Phys. A977 (2018) 146-207. doi: 10.1016/j.nuclphysa.2018.05.007

[63] Kang, Y. et al., Crystal structure of rhodopsin bound to arrestin by femtosecond X-ray laser. Nature 523, 561 (2015). doi: 10.1038/nature14656

[64] Bussmann, M., et al., Radiative Signatures of the Relativistic Kelvin-Helmholtz Instability In: Proceedings of SC13: International Conference for High Performance Computing, Networking, Storage and Analysis 5-1 (2013). doi: 10.1145/2503210.2504564

[65] Hilz, P., et al., Isolated proton bunch acceleration by a petawatt laser pulse Nature Communications 9, 423 (2018). doi: 10.1038/s41467-017-02663-1

[66] Hilger, A. et al., Tensorial neutron tomography of three-dimensional magnetic vector fields in bulk materials, Nature Communications 9, 4023 (2018). doi: 10.1038/s41467-018-0659

[67] Heller, T., et al., Harnessing Billions of Tasks for a Scalable Portable Hydrodynamic Simulation of the Merger of Two Stars, The International Journal of High Performance Computing Applications (2019). doi: 10.1177/1094342018819744

[68] Hartmann, N. et al., Attosecond time–energy structure of X-ray free-electron laser pulses, Nature Photonics 12, 215 (2018). doi: 10.1038/s41566-018-0107-6

[69] Pfeiffer, S. et al., Precision feedback control of a normal conducting standing wave resonator cavity, Phys. Rev. Accel. Beams 21, 092802 (2018). doi: 10.1103/PhysRevAccelBeams.21.092802

[70] https://github.com/ComputationalRadiationPhysics/picongpu

[71] https://github.com/ocelot-collab