Research Field Matter

Proposal for a Helmholtz Research Programme

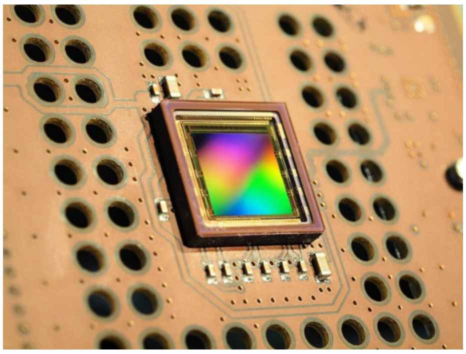
Matter and Technology

for the third funding period, 2015 – 2019

Volume I

Participating Centres:	Deutsches Elektronen Synchrotron DESY Forschungszentrum Jülich GSI Helmholtzzentrum für Schwerionenforschung Helmholtz-Zentrum Berlin für Materialien und Energie Helmholtz-Zentrum Dresden-Rossendorf Karlsruher Institut für Technologie
Programme Speaker:	Ties Behnke (DESY)

Explanation of the cover pictures



CMOS image sensor board of the UFO project on ultrafast X-ray tomography. The project aims to develop a workflow connecting high-throughput detector readout to GPU accelerated image reconstruction. CMOS imagers combine charge-sensitive pixel arrays with highly integrated electronics in one monolithic piece of silicon. They will find applications at synchrotrons and FELs as well as in inner tracking detectors in nuclear and particle physics experiments.

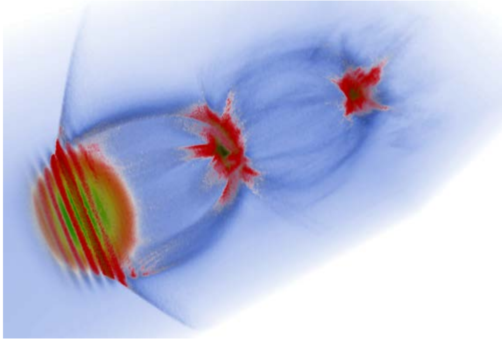
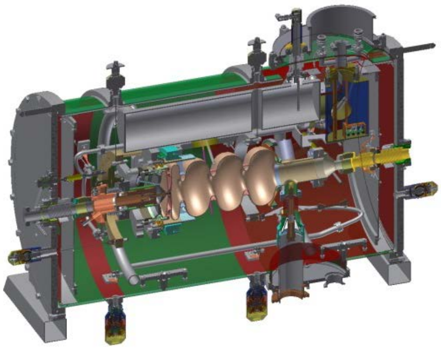


Image of a three-dimensional Particle-in-Cell simulation (PIConGPU) of a laser pulse with relativistic intensity propagating in a gas plasma. The pulse excites a nonlinear wake supporting local acceleration fields exceeding 100 GeV/m while electrons are self-injected at the rear of the wake



3D cutaway view of the world's first operational superconducting photo injector installed at an accelerator user facility (ELBE). The centerpiece is a 3.5-cell Niobium RF resonator with a normal conducting Cs2Te photocathode. The injector delivers a high brightness electron beam and operates in full CW mode.

Helmholtz Association

Mission Statement

We contribute to solving grand challenges
which face society, science and industry
by performing top-rate research in strategic programmes
in the fields of Energy, Earth and Environment, Health,
Key Technologies, Structure of Matter,
Aeronautics, Space and Transportation

We research systems of great complexity
with our large-scale facilities and scientific infrastructure,
cooperating closely with national and international partners.

We contribute to shaping our future
by combining
research and technology development
with perspectives
for innovative applications and
provisions for tomorrow’s world.

Participating centres

Deutsches Elektronen-Synchrotron (DESY)

Prof. Dr. Helmut Dosch
Notkestr. 85
22607 Hamburg
Phone: +49 40 8998 3000
Fax: +49 40 8994 4304
Email: desy-director@desy.de

Forschungszentrum Jülich (FZJ)

Prof. Dr. Sebastian M. Schmidt
Wilhelm-Johnen-Str.
52428 Jülich
Phone: +49 2461 61 3901
Fax: +49 2461 61 2640
Email: s.schmidt@fz-juelich.de

GSI Helmholtzzentrum für Schwerionenforschung (GSI)

Prof. Dr. Dr. h.c. mult. Horst Stöcker
Planckstr. 1
64291 Darmstadt
Phone: +49 6159 71 2648
Fax: +49 6159 71 2991
Email: h.stoecker@gsi.de

Helmholtz-Zentrum Berlin für Materialien und Energie (HZB)

Prof. Dr. Anke Kaysser-Pyzalla
Hahn-Meitner-Platz 1
14109 Berlin
Phone: +49 30 8062 43812
Fax: +49 30 8062 42047
Email: anke.pyzalla@helmholtz-berlin.de

Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Prof. Dr. Dr. h. c. Roland Sauerbrey
Bautzner Landstraße 400
01328 Dresden
Phone: +49 351 260 2744
Fax: +49 351 260 2700
Email: r.sauerbrey@hzdr.de

Karlsruher Institut für Technologie (KIT)

Prof. Dr. Holger Hanselka
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen
Phone: +49 721 608 22000
Fax: +49 721 608 26123
Email: holger.hanselka@kit.edu

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Position Paper of the Research Field MATTER in the Helmholtz Association

Coordinator of the Research Field:
Prof. Dr. Helmut Dosch (DESY)

Funding Period 2015-2019

1. SCIENTIFIC CHALLENGES

A premier mission of the Research Field MATTER is the deepest possible understanding of matter and materials in order to face the grand challenges of our society. The Helmholtz Centres of the Research Field will further expand our molecular knowledge base on the structure and function of matter, which is a prerequisite for the controlled design of tailored materials and drugs for tomorrow.

During the last decades we have implemented a solid experimental, technical and theoretical basis for the next steps towards controlling matter and energy on the quantum level. This will finally revolutionise our understanding of molecular functions and quantum processes and enables us to devise novel materials with tailored functions and to orchestrate chemical and biochemical processes at the interface of physics to chemistry and biology.

We must advance our understanding of the universe at the largest and smallest scales and under extreme nuclear conditions. We venture to find a better understanding of matter that is composed of quarks and gluons, insights into the origin of mass, into the nature of the most energetic cosmic rays and to identify Dark Matter. Hence, our instruments range from astroparticle observatories to high-energy particle and ion accelerators and colliders.

In the coming years the research and development activities of the Helmholtz Centres that collaborate within the Research Field MATTER have to cope with several urgent and vexing problems, which range from our fundamental understanding of matter and the universe to our ability to control matter and materials down to the level of electrons and spins. The major objectives to be addressed by the Research Field MATTER are

- a better understanding of the origin and evolution of the universe and all matter and antimatter therein,
- the further exploration of the variety of forms of cosmic and exotic matter in the laboratory, and
- a better understanding and controlling of the function of materials at the level of atoms and electrons, including the control of the electronic and molecular processes at the real time scale and thus contributing to the design of novel materials and drugs.

These ambitious objectives critically depend on the Research Field's core competence in the design and operation of accelerator-based “super-microscopes” with highest spatial and temporal resolution, of advanced neutron, ion and high-field facilities and of novel particle, astroparticle and photon detectors as well as on theoretical concepts of the highest sophistication.

The modern research facilities of the Research Field support leading-edge research and its transfer to society ranging from physics, chemistry and biology to materials science and medicine, with applications in energy, environment, key technologies and health. They are high-tech platforms which drive technology, attract scientists from all over the world and offer unique interdisciplinary and scientifically challenging environments for young researchers.

2. THE CORE COMPETENCES OF THE RESEARCH CENTRES

Seven Helmholtz Centres contribute to the Research Field MATTER: Deutsches Elektronen-Synchrotron (**DESY**) in Hamburg and Zeuthen, Forschungszentrum Jülich (**FZJ**), Helmholtzzentrum für Schwerionenforschung (**GSI**) in Darmstadt with its two Helmholtz Institutes (HI) in Mainz and Jena, Helmholtz-Zentrum Berlin für Materialien und Energie (**HZB**), Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research (**HZG**), Helmholtz-Zentrum Dresden-Rossendorf (**HZDR**), as well as Karlsruhe Institute of Technology (**KIT**).

DESY, one of the world's leading accelerator centres, operates PETRA III and the X-ray laser FLASH and hosts the European X-ray Laser XFEL, and is a key partner in international projects, such as the LHC, IceCube and the planned CTA. DESY has a focused research programme in accelerator development, photon science and particle and astroparticle physics. DESY attracts more than 3,000 scientists from over 40 countries annually using the DESY infrastructure.

The research mission of Jülich **(FZJ)** is to contribute to science and technology world-wide in the Research Fields of ENERGY, CLIMATE, MATTER and KEY TECHNOLOGIES. Within MATTER – building on the experience with COSY - Jülich takes over a leading role in the hadron physics programme, e.g. by constructing, building and using HESR at FAIR. It also pursues its strategic objective to fully utilise and optimise the potential of dedicated neutron scattering instruments at national and international large-scale facilities.

Mission and key competences of **GSI** are the construction and operation of large ion beam accelerators as well as their exploitation for research into hadron and nuclear physics, atomic and plasma physics, materials research and radio biology. The major focus of GSI during PoF-III will be the construction and commissioning of the Facility for Antiproton and Ion Research FAIR together with national and international partners.

Operating two large research infrastructures, the neutron source BER II and the light source BESSY II, **HZB** is one of just a few centres worldwide supporting the complementary use of neutrons and photons for research on structure and function of materials, therefore serving more than 3,000 international users per year. HZB combines its expertise in accelerator and instrument development with a strong material and energy research programme and contributes to the Research Fields MATTER and ENERGY.

In the Research Field MATTER **HZDR** (Helmholtz member since 2011) focuses on the research on the structure, dynamics and function of matter, physics and material science with ion beams, research and development for new accelerator and detector technologies and leading research with the highest electromagnetic fields. It runs the Ion Beam Centre (IBC), the Dresden High Magnetic Field Laboratory (HLD) and the ELBE accelerator with secondary radiation sources. HZDR is active also in the Research Fields ENERGY and HEALTH.

The research at **HZG** covers materials science with an emphasis on advanced engineering materials, materials research with synchrotron radiation and neutrons, biomaterials for regenerative medicine, as well as climate and environmental research focussing on coastal dynamics and its natural and anthropogenic drivers. The HZG is actively involved in the Research Fields KEY TECHNOLOGIES, EARTH AND ENVIRONMENT and MATTER. Within MATTER HZG provides unique research infrastructures for materials research at PETRA III and FRM II.

The Karlsruhe Institute of Technology **KIT** contributes to the Helmholtz Research Fields KEY TECHNOLOGIES, EARTH AND ENVIRONMENT, ENERGY and MATTER. Within MATTER, KIT concentrates on (i) elementary particle physics including the Tier-1 data centre GridKa, (ii) astroparticle physics with neutrino physics, the search for Dark Matter and cosmic ray research, (iii) the synchrotron radiation facility ANKA, and (iv) advanced detector and accelerator developments.

3. OVERALL GOALS OF THE RESEARCH FIELD MATTER

The Helmholtz Centres contributing to the Research Field MATTER will continue their efforts to conduct their own research as well as the construction and operation of Helmholtz Large-scale Facilities; these two categories are specified as *Leistungskategorie I (LK I)* and *Leistungskategorie II (LK II)*, respectively.

The Helmholtz Centres cooperating in MATTER will

- carry out research to explore the structure and function of matter at the highest finesse and to further develop the necessary research infrastructure in order to maintain a leading international role in this ambitious Research Field,
- strive for more strategic cooperations with neighbouring scientific disciplines, university groups and with international partner institutes and laboratories, and
- join forces in the development of accelerator technologies and novel accelerator concepts, advanced detectors and large-scale data management.

The latter effort should establish new Helmholtz technology hubs, which coordinate R&D on a national level and foster new cooperations in Europe and worldwide.

The Research Field MATTER selectively expands its expertise and infrastructure in order to explore new areas in the investigation of matter. The Helmholtz Centre Dresden-Rossendorf recently joined the Research Field contributing novel competences to the exploration of matter under extreme conditions. The two international facilities XFEL and FAIR are under construction. They will offer unprecedented opportunities in the exploration of the structure and function of matter.

In order to tackle the scientific challenges mentioned before, the contributing Helmholtz Centres have decided to work together within a new programme structure, which maximises cross talk between disciplines and fosters interdisciplinary use of the research infrastructure across the Helmholtz Research Fields. The new Research Field MATTER will be organised in three programmes, MATTER AND THE UNIVERSE, FROM MATTER TO MATERIALS AND LIFE and MATTER AND TECHNOLOGIES.

4. THE CONTRIBUTION OF THE PROGRAMMES

In the third period of programme-oriented funding (PoF) of the Helmholtz Association, starting in 2015, the Helmholtz centres will set new research priorities within the three programmes as described in the following.

Due to the strong focus of GSI towards the construction of FAIR, the operation of the existing ion facilities will be reduced, and the activities of the GSI Darmstadt site will not participate in the evaluation process. The same applies to the FAIR contribution of FZJ. An additional special fact is the important task of DESY for commissioning and operation of the XFEL accelerator, committing a substantial fraction of its own resources to this demanding effort.

4.1. PROGRAMME MU: MATTER AND THE UNIVERSE [DESY, FZJ, GSI, KIT]

The task of the programme MATTER AND THE UNIVERSE is literally to connect quarks and leptons to the cosmos. Disciplines such as elementary particle physics, astroparticle physics, the physics of hadrons and nuclei, atomic and plasma physics join forces to find answers to fundamental questions, including “What is the origin, structure and future of the Universe?”, “What are the building blocks of matter and how do they interact?” or “How did complex structures form?”.

These questions are jointly addressed by researchers working in large international collaborations. The communities are connected in vivid networks and three Helmholtz Alliances among Helmholtz Centres, universities and other research centres. They have excellent and unique infrastructures at their disposal, including e.g. the Large Hadron Collider LHC at CERN, the accelerator complex and future FAIR facility at GSI and numerous large detectors, underground laboratories or observatories for viewing deep into the cosmos. MATTER and The Universe is organised in three topics as described below.

Fundamental Particles and Forces [DESY, KIT]

This topic focuses on our understanding of the fundamental building blocks of matter and the forces between them. Emphasis is put on

- unravelling the mechanism of electroweak symmetry breaking for which the recently discovered Higgs-like particle is believed to play a key role and which is the basis for generating mass of fundamental particles,
- the unification of forces and the search for extra dimensions, and
- the understanding of the matter-antimatter asymmetry in the universe.

Strategic goals are to strengthen the role of the Helmholtz Association and Germany as a whole in international large-scale projects such as the LHC and a future Linear Collider and to foster the role of DESY as a national centre for particle physics in Germany. This is exemplified by the successful Alliance *Physics at the Terascale*, whose activities should be continued. The most important scientific and technological goals of the next years are

- operation and optimisation of the LHC and its detectors,
- enhancement of the data analysis efforts,
- contribution to the upgrades and improvements of the detectors ATLAS and CMS,
- operation and extensions to the Tier-1 data centre GridKa, the Tier-2 centres and to the National Analysis Facility (NAF),
- further strengthening of the leading position in particle theory in the four main fields particle phenomenology, cosmology, string theory and lattice gauge theory, and

- exploitation of the DESY infrastructure and joint contributions together with German university groups towards new international projects within the context of the European Strategy for Particle Physics.

These efforts are mandatory to fully exploit the German investments in LHC, to meet the upcoming requirements within the worldwide LHC Computing Grid and to ensure that the data analysis in Germany remains competitive. Lattice gauge computations are made in close collaboration with the Neumann Institute for Computing (NIC). Examples for emerging international projects are a future Linear Collider and the Belle Experiment at the SuperKEKB facility in Japan, which is currently under construction.

LK II facilities within this topic are a Tier-2 Data centre at DESY and the Tier-1 Data Centre GridKa at KIT.

Cosmic Matter in the Laboratory [FZJ, GSI]

This programme topic is dedicated to the following research themes:

- quark-gluon dynamics and phases in very dense and/or very hot nuclear matter,
- the dynamics, structure and stability of hadrons, the mechanism of hadronisation, and strong CP-violation, and
- the generation of complex clusters of elementary matter and chemical elements and the limits of stability for exotic nuclei, the symmetry between matter and antimatter

In detail, we intend to achieve the following scientific and technological goals:

- top priority is the realisation and commissioning of the GSI contributions to the FAIR modules 0 to 3. FAIR will foster and extend the leading role of Helmholtz and Germany in the above research fields for the next two to three decades.
- phased construction and operation of the FAIR Tier-0 analysis centre (Green IT Cube), the theory HPC Cluster and the Tier-2 analysis centre for ALICE;
- besides FAIR construction and R&D for FAIR: reduced in-house research and user operation at GSI and FZJ, with a focus on:
- relativistic heavy ion physics at GSI (HADES) and CERN/LHC (ALICE);
- hadron physics (FZJ/GSI); nuclear structure and nuclear astrophysics (GSI)
- in-house research (LK I) at the Helmholtz-Institute Mainz will focus on preparatory R&D activities for FAIR, accelerator development and superheavy element research.

GSI and FZJ play a leading role in the construction and commissioning of the FAIR accelerators. In addition, both centres make leading contributions to the experimental installations of the four FAIR collaborations APPA, CBM/HADES, NUSTAR and PANDA, which altogether comprise more than 2,500 scientists. Sustained networking with German universities and other national and international research institutes will be guaranteed by the Helmholtz Alliance *Cosmic matter in the laboratory (ExtreMe Matter Institute,* EMMI), the LOEWE-Helmholtz Centre of Excellence (HICforFAIR) and the Helmholtz Institutes in Mainz and Jena (APPA and the Helmholtz Institute Jena are embedded into the programme *From Matter to Materials and Life*). To accomplish this, EMMI and HICforFAIR need to be funded in a sustained way. This also applies to the research training of young scientists in the Helmholtz Graduate School “HiRe for FAIR”.

For the previous Large-scale Facilities (LKII) of this topic, FZJ-COSY and GSI-accelerators, only very reduced user operation will be possible due to the realisation of FAIR.

Matter and Radiation from the Universe [DESY, KIT]

Astroparticle physics in Germany has developed an internationally distinct scientific profile with the high visibility of the Helmholtz Association. This programme topic concentrates on key aspects of astroparticle physics. The scientific goals include

- understanding the origin and properties of the most energetic cosmic particles,
- the establishment of multi-messenger astroparticle physics using high-energy neutrinos, photons and charged particles,

- identification and understanding of Dark Matter, and
- the clarification of the properties of neutrinos, in particular their mass.

The Helmholtz programme has shaped astroparticle physics on an international level and strengthened the European coordination. In the next programme period we will pursue this architectural role with the following endeavours:

- extension of the scientific portfolio in the analysis and theory sectors,
- further development of the Pierre Auger Observatory in Argentina, IceCube at the South Pole, KATRIN at KIT
- intensified search for Dark Matter particles in a global experiment, which combines the capabilities of EDELWEISS, EURECA and SuperCDMS,
- development, preparation and construction of the Cherenkov Telescope Array (CTA) and participation in current gamma-ray observatories H.E.S.S., MAGIC and VERITAS,
- explorative studies in neutrino physics and the development, preparation and construction of novel detection systems for Dark Matter and cosmic rays.

Within the Helmholtz Alliance of Astroparticle Physics, KIT and DESY will extend the cooperation with 15 German universities, three Max Planck Institutes and five international partners and strive for a sustained future of the network.

A distinctive feature of this programme topic is that our unique large research instruments are often not hosted at established laboratories but at remote locations.

4.2. PROGRAMME MML: FROM MATTER TO MATERIALS AND LIFE [DESY, FZJ, GSI, HZB, HZDR, HZG, KIT]

This programme is devoted to analysing and modifying the structure, dynamics and function of matter and materials by the use of large-scale facilities in close collaboration with users from academic science and industry. Current challenges include

- the understanding of transient states in solid materials, molecules and biosystems,
- an improved knowledge of complex matter and the ability to derive intelligent functionalities,
- the rational design of new materials for energy, transport and information technologies,
- the improvement of the molecular design of agents,
- the investigation of the structure and function of matter far from equilibrium,
- the investigation of matter and materials in strong electromagnetic fields.

This research is closely connected to the user-operation of a wide range of research infrastructures encompassing photon, neutron and ion sources, high-magnetic field facilities and high power lasers. These large-scale facilities provide unique research opportunities for national and international research groups as well as for cooperations between Helmholtz Research Fields. Within this framework the LK II infrastructures ANKA, BER II, BESSY II, ELBE, FLASH, GEMS, HLD, IBC, JCNS and PETRA III as well as the contributions to international facilities such as the European XFEL and in the future FAIR and ESS (planned) will be the essential basis of the research conducted in this programme. Therefore, they are presented as an integral part of the programme proposal. The programme is organised as an in-house research topic and four topics, which focus on operation and construction of all aforementioned research infrastructures grouped by the probe they are providing (photons, neutrons, ions, high electromagnetic fields). These five topics are presented in the following.

In-house research on structure, dynamics and function of matter at large-scale facilities [DESY, FZJ, GSI, HZB, HZDR, HZG, KIT]

This topic comprises the in-house research of all contributing centres at their large-scale facilities. Excellent in-house research is essential for maintaining the methodical competence needed for designing, building and operating world-leading experiments according to the needs of the users. Based on intense cooperation between the Helmholtz centres these activities are focused on the following research themes:

- Extreme states of matter: From cold ions to hot plasmas,
- Quantum condensed matter: Magnetism, superconductivity, and beyond,
- Materials and processes for energy and transport technologies,
- Nanoscience and materials for information technologies, and
- Soft matter, health and life sciences.

This research is conducted in close collaboration with other Helmholtz Research Fields, most prominently with KEY TECHNOLOGIES, ENERGY and HEALTH. The Helmholtz Institute Jena is integrated in “Extreme states of matter: From cold ions to hot plasmas”. A strengthening of the in-house research is also achieved by implementing new cross-programme research activities, which often build on the PoF II Helmholtz portfolio process.

The following four sections describe the main goals of the Large-scale Facilities operated by the Helmholtz centres as user facilities contributing to the programme.

Facility Topic: Research on matter with brilliant light sources [DESY, HZB, HZG, KIT]

The research at brilliant synchrotron sources and free-electron lasers ranges from basic science to applied science and engineering. The tuneability of synchrotron radiation allows for element-specific investigations and photons of a defined polarisation state are powerful tools for the investigation of correlated electron systems. Photon sources with ultrashort pulses and high coherence allow new insights into static and dynamic effects on a wide range of length and time scales, into the atomic structure of partially ordered matter, and into materials properties relevant to nanoscience and technology. With the photon sources ANKA, BESSY II, PETRA III, FLASH and the contribution to the European XFEL Helmholtz provides first-class research infrastructures in Germany covering the complete spectral range, which attracts users from all over the world. Future activities will focus on

- the contribution to construction, commissioning and user operation of XFEL,
- the operation and extension of PETRA III (phase II and phase III Beamlines) and of FLASH (seeding, cw-operation, improved laser undulators),
- the continuous upgrade of BESSY II and its instruments and the development of BESSY II into a variable pulse length storage ring BESSY^{VSR}, and
- a full-energy-injector upgrade of ANKA to allow top-up operation and the provision of intense short-pulse radiation in the full ANKA spectral range.

Facility Topic: Neutrons for research on condensed matter [FZJ, HZB, HZG]

Due to the large accessible space-time window, neutrons provide a microscopic insight into highly complex phenomena and thus enable the understanding of the resulting functionalities. With the next-generation megawatt spallation sources a neutron peak flux will be achieved, which strongly surpasses existing sources and will therefore significantly broaden the application of neutron methods.

Germany has one of the most productive neutron user communities and operates with the BER II and the FRM II two of the most important neutron facilities worldwide. With the operation of the neutron sources BER II and FRM II and the contribution to the first American megawatt spallation source SNS the Helmholtz Association is one of the internationally leading players in neutron science worldwide and provides unique experimental opportunities to German and international users. BER II will stay in operation until 2020. The main goals are:

- extension of the cooperation with the TUM concerning the FRM II (JCNS and GEMS),
- operation of a selected instrument suite at BER II at the highest possible standards until 2020.

The design and construction of experiments at the future European spallation source ESS in Lund, Sweden, is scheduled for the same time frame as PoF-III. The operation of ESS will presumably start in PoF IV. In line with their strategies and the available resources the Helmholtz centres FZJ and HZG will contribute to ESS instruments.

Facility Topic: Physics and materials science with ion beams [GSI, HZDR]

The ion facilities of GSI and HZDR are complementary and provide outstanding experimental capabilities for atom physics, plasma physics and material science. The broad spectrum includes precision experiments on fundamental principles of physics in extreme electromagnetic fields, research on matter under extreme pressures, densities and temperatures, as well as applied research in microelectronics, information technology, and nanoscience.

The main goals are:

- construction of APPA experiments at FAIR,
- concentration of the user service on selected new beam lines (HITRAP, M-Branch) and the high power laser PHELIX (GSI),
- operation of the Ion Beam Centre (HZDR) for ion beams for controlled modification and structuring of materials on the nano and subnano scale,
- development of high-resolution, standard-free chemical analysis for resource technology (HZDR).

Facility Topic: Research at highest electromagnetic fields [GSI, HZDR]

Due to new technological developments in recent years electromagnetic fields of up to now inaccessible magnitude have become experimentally feasible. In extreme magnetic fields new states of matter are explored. In addition compact high-power laser systems open up additional fields of research. Apart from answering basic questions on matter in extreme fields, the ultrashort pulses allow the investigation of the fastest processes on the atomic scale. The main goals are:

- operation and further development of the High magnetic field Lab Dresden (HLD) and its European integration,
- operation and development of ELBE for the coupling of ultra-intense lasers with accelerators and beam-driven strong field sources (FELBE, THz, DRACO, PENELOPE),
- operation of PHELIX for the investigation of hot dense matter,
- development of the Helmholtz beamline at XFEL (and planning for FAIR),
- establishment of new laser-based sources for X-ray and particle beams.

4.3. PROGRAMME MT: MATTER AND TECHNOLOGIES

This programme is a new initiative of the Research Field to bundle the technological competences of the different Helmholtz centres and to develop a coherent and coordinated strategy in this important field. The programme will work on the following key challenges:

- exploration and development of novel accelerator technologies for future applications,
- development of novel detector technologies for a broad range of applications,
- development and initiation of the knowledge transfer between the Helmholtz centres, other research organisations and industry.

This programme will enhance the international reputation of the Helmholtz Association for the development of future enabling technologies. It will be structured into the two topics Accelerator Research and Development and Detector Technologies and Systems. These topics emerge from the portfolio topics ARD (Accelerator Research and Development) and Detector Technologies and Systems Platform. The programme will seek the close cooperation with universities and other research centres. It will actively develop and expand the cooperation with other research fields within the Helmholtz Association.

Accelerator Research and Development [DESY, FZJ, GSI, HZB, HZDR, KIT]

The topic is focused on new developments in accelerator physics and technology, i.e.

- superconducting RF technology and high-brightness CW beam sources,
- concepts and technologies for hadron accelerators and storage rings,
- pico-second and femto-second electron and photon beams, and
- high-gradient acceleration with lasers and plasmas.

All four subjects are closely related to ongoing activities within the Helmholtz Association, but they also explore possibilities well beyond those of current systems and should open the way to new applications. Close cooperation and networking between the centres is supported by the possibility to utilise existing facilities and projects under construction for joint R&D activities, such as PITZ at DESY, ELBE at HZDR, COSY at FZJ, FLUTE at KIT and BERLinPro at HZB.

Detector Technology and Systems [DESY, FZJ, GSI, HZDR, KIT]

The topic aims to enable to perform cutting-edge science through investigation, development and characterisation of innovative detector technologies and systems. This includes R&D on sensors and the associated read-out electronics for high precision measurements of photons, charged particles and ions. The research objectives are driven by the specific needs of the current and future facilities and research programmes as outlined above. Emphasis is put in particular on

- technologies for highly integrated, pixelated detector systems,
- innovative sensors including semiconductor and other sensing media,
- low-noise, low-power and cryogenic detectors,
- ultra-fast data transfer and data reconstruction techniques, and
- development and characterisation of selected detector systems.

4.4. INTERDISCIPLINARY TOPIC: DATA MANAGEMENT AT LARGE-SCALE FACILITIES

Large-data management is – and will become in future even more so – a key enabling technology of the Research Field MATTER. Efficient storage methods and rapid access to massive data sets, as created notably at the LHC, at the European XFEL and at FAIR, pose serious challenges to future data technologies, which have to be tackled by a joint effort of all experts in the Research Field in order to assure an efficient and reliable analysis of the complex scientific data. The precise demands and technical problems will only emerge in the coming years directly at the various experiments and facilities. In turn, the Research Field has decided to organise this effort as a cross-programme topic within the Research Field in order to leverage and combine the expertise from the various disciplines in MATTER. This interdisciplinary topic will closely cooperate with the cross-programme **Large-Scale Data Management**, which integrates other Helmholtz disciplines, coordinated by the Research Field Key Technologies (topic 5a below).

5. Cross-Programme Research Objectives and Topics

The MATTER programmes are involved in the following cross-programme activities and initiatives:

a) Cross-Programme Initiative **Large-Scale Data Management:** Secure, efficient and sustainable management of large-scale data (Big Data) as well as its analysis with appropriate methods, tools and systems are technological challenges for all research disciplines. Aims of the cross-programme initiative are the Helmholtz-wide coordination of Big Data activities and the constitution of a research bridge across the Helmholtz programmes and Research Fields on the basis of the portfolio extension LSDMA.

b) Cross-Programme Activity **Structural Biology:** This cross-programme activity should promote and exploit synergies in structural biology by supporting networking of the unique research infrastructures of the Helmholtz Association (such as the brilliant synchrotron radiation sources of the Research Field MATTER) and the existing excellent expertise to develop integrated structural biology. This will open new frontiers for biomedical research.

c) Cross-Programme Activity **Materials for Energy Technologies:** This cross- programme activity aims at advanced materials design and testing for future energy conversion and storage applications. A key aspect will be the development of simulation methods to understand material behaviour on different length scales and of adequate models for material synthesis and processing as well as for manufacturing of components. In combination with novel high-resolution *in-situ* characterisation methods, a comprehensive understanding of the properties and functions of new energy materials will be achieved.

d) Cross-Programme Initiative **Technology and Medicine:** Medical conditions require technologies for an individually tailored treatment of each patient,therefore new adaptive systems are needed. The research will focus on the topics “Advanced imaging methods – Smart tracer”, “Multifunctional tubular support systems–stents” and “*in-vivo* behaviour of polymeric biomaterials”, and is based on the Portfolio Topic “Technology and Medicine”. It combines activities of the Research Fields KEY TECHNOLOGIES, HEALTH and MATTER.

6. Research objectives of particular national significance

User Operation of Large-scale Facilities: The Research Field operates and continuously improves its facilities for the dedicated use by university groups and research organisations, which have integrated this unique research infrastructure in their various research programmes in all fields. These range from atomic physics, molecular chemistry, structural biology, advanced materials science, nanotechnology to geology and matter under extreme conditions. These successful cooperations will be further strengthened and extended to an even broader scientific community. The further strong support of the universities by the federal project funding will continue to play a key role.

Strategic Cooperations in International Large-scale Projects: The Research Field MATTER is the national hub, which coordinates the German cooperation in several international large-scale projects such as the Large Hadron Collider at CERN and the Pierre Auger Observatory for cosmic rays in Argentina as well as the new international projects XFEL and FAIR on German ground, which are currently under construction.

Development of Cutting-Edge Technologies for New Accelerators, Detectors and Data Management Systems: Current and future technologies ranging from fundamental research to advanced-materials design, health and security will critically hinge on more efficient particle accelerators and highly sensitive detection systems and on our ability to handle massive amounts of data. The Research Field MATTER concentrates all necessary knowledge and experience to further push the limits of these three enabling technologies and to develop nationally coordinated technology platforms.

7. NETWORK STRATEGIES OF THE RESEARCH FIELD MATTER

Research and education in the Research Field MATTER are strongly based on national and international scientific networks, in particular on

- dedicated interdisciplinary user operation of the research infrastructure (LK II) based on peer review and project funding,
- interdisciplinary cooperation within the new Helmholtz Cross-Programme Activities and Initiatives (see section 5),
- Helmholtz Alliances (Physics at the Terascale, Astroparticle Physics, Cosmic Matter in the Laboratory),
- continued integration of the Helmholtz Institutes Jena and Mainz into the mission of the Research Field,
- regional cooperation with university partners, and
- strategic cooperation within the Röntgen-Angstrom Cluster (German-Swedish Cooperation in Materials Science and Structural Biology) and Ioffe-Röntgen-Institute (German-Russian Cooperation in Bio-Nano-Materials and Key Technologies).

8. FURTHER STRATEGIC GOALS OF THE RESEARCH FIELD MATTER

Promotion of the next generations of scientists: The Research Field MATTER offers a unique research infrastructure for education and training of students and for scientists at the beginning of their career. This potential will be further developed through strategic alliances with universities. The Research Field is planning to further implement new Helmholtz Colleges and Graduate Schools, Helmholtz Young Investigator groups and initiatives for W3/W2 professors.

Gender equality: To keep the Research Field at the forefront of science it is mandatory to promote talents and to offer equal opportunities to women and men from the very beginning. In the Research Field MATTER this starts as early as in school labs or programmes like MINT to especially foster the interest of girls and women in natural sciences. Flexible working hours, re-entry options and support for spouses and for childcare must become routine to ensure a productive and dedicated future workforce.

Research transfer as an innovation goal: Efficient knowledge transfer to industry is recognised by the Helmholtz MATTER Centres as a future challenge. The new programme MATTER AND TECHNOLOGIES focuses on those key enabling technologies and is striving to establish an intensified exchange with the industrial sector.

Transfer to the public sphere / outreach: Science and technology play an ever-increasing role in society, and research in the field of MATTER is deeply anchored in the public perception of science. Many messages can be conveyed through the current fascination with science: the fact that science drives innovation, that we do research for a sustainable future and that we offer excellent training opportunities in international environments, which will have a direct impact on the workforce of tomorrow.

RESEARCH FIELD COSTS

in 1,000 EUR	**DESY**	**FZJ**	**GSI**	**HZB**	**HZDR**	**HZG**	**KIT**	**Total**
Matter and the Universe	36,534	4,665	6,905 *				15,582	**63,686**
From Matter to Materials and Life	22,394	6,399	4,055 *	6,022	15,442	2,328	2,403	**59,043**
Matter and Technology	18,679	1,521	2,150 *	7,143	9,828		2,683	**42,005**
LK II - TIER II	5,771							**5,771**
LK II - FLASH	41,756							**41,756**
LK II - PETRA III	72,244							**72,244**
LK II - JCNS		18,888						**18,888**
LK II - BER II				28,050				**28,050**
LK II - BESSY II				39,876				**39,876**
LK II - ELBE					8,914			**8,914**
LK II - HLD					6,026			**6,026**
LK II - ISZ					7,863			**7,863**
LK II - GEMS						6,000		**6,000**
LK II - ANKA							19,881	**19,881**
LK II - GridKa							10,252	**10,252**
FAIR (under construction)		14,572 **	87,081 **					**101,653**
XFEL (under construction)	34,756							**34,756**
Total	**232,134**	**46,045**	**100,191**	**81,091**	**48,073**	**8,328**	**50,801**	**566,663**

*) Contributions by the GSI Helmholtz Institutes in Mainz and Jena, and funding envisaged for a sustained continuation of the cooperation and graduate training programmes: HIC for FAIR, HGS-HIRe and the Helmholtz-Alliance EMMI.

**) The contributions by FZJ and GSI to the construction of FAIR are exempted from the PoF evaluation.

Research Field Matter

Proposal for a Helmholtz Research Programme

Matter and Technology

for the third funding period, 2015 – 2019

Volume I

Participating Centres:	Deutsches Elektronen Synchrotron Forschungszentrum Jülich GSI Helmholtzzentrum für Schwerionenforschung Helmholtz-Zentrum Berlin für Materialien und Energie Helmholtz-Zentrum Dresden-Rossendorf Karlsruher Institut für Technologie
Programme Speaker:	Ties Behnke (DESY)

II. PROGRAMME “MATTER AND TECHNOLOGY”

1 Overview

Research in “Matter” relies heavily on two technological pillars: accelerators and detectors. The operation and exploitation of accelerators for science in the two programmes “Matter and the Universe” and “From Matter to Materials and Life” is a central objective. Detectors are the tools needed at these infrastructures to do the science and to learn about the fundamental laws of nature. Beyond “Matter” these technologies play a key role both in research and in society at large.

With the new programme “Matter and Technologies” the research field will build a centre of excellence in accelerator and detector development. Research and development in accelerator and detector physics and technology has a long tradition in the Helmholtz Association, and has always been a prerequisite for the successful research in Helmholtz. Germany is one of the leaders in accelerator and detector technology and it is the goal of this programme to maintain and expand these capabilities. With the new programme synergies between the different centres will be better exploited.

A key element of the new programme is to develop technological know-how and contribute to the solution of the most important challenges in the field. The goals of the programme are oriented towards the future needs of the research field. A network of technological competence and innovation will be developed across the research field and beyond. Nearly all research centres which participate in “Matter” contribute to the new programme, extending the cooperation between the centres which already exists at the moment. With the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) a new research centre with a significant and very relevant technological portfolio has entered the Helmholtz Association and contributes centrally to the new programme. The programme closely collaborates with universities and other research organisations within Germany and beyond. It will develop and intensify ties with relevant industries.

The programme is structured into two topics, accelerator research and development (ARD) and detector technology and systems (DTS). The programme participates in the cross programme activity “Data Management at Large Scale Infrastructures” and the cross programme initiative “Large-Scale Data Management and Analysis” (LSDMA).

1.1 Challenges, Objectives and Strategy

The programme “Matter and Technology has been defined to sharpen the scientific profile of the research field, is part of an overall strategy to ensure international competitiveness of the research field, to maximise synergies and to exploit scientific overlap between neighbouring fields.

The scientific objectives of the programme “Matter and Technology” are the result of a careful and intense discussion process which started during the previous funding cycle. Within the research field the need to strengthen advanced R&D on accelerator and detector technologies has been identified as a high priority goal. During the current funding period the research field initiated two projects as part of the portfolio process of the Helmholtz Association. The accelerator research and development (ARD) initiative and the detector technologies and systems platform (DTS) both received start-up funds to establish research in this area and start to build up the necessary structure. A focus of these first years was on establishing networking and starting selected ambitious research projects. With the new funding cycle this startup phase is transformed into a programme within the research field “Matter”, based on a broad consensus among the partners in “Matter”.

The programme has been designed to address the main technological challenges the field is facing. It is defined with a long-term perspective. A central role in the definition of the priorities is played by the large research infrastructures which are available to the Helmholtz Association. The programme has also been conceived as a dynamic, evolving programme. Technologies develop rapidly in today’s world, new ones emerge and new technological questions and challenges arise. The programme will take up the new challenges and integrate them into the existing structure and workplan.

Close cooperation with industrial partners is of essential importance. Many of the technologies developed at laboratory level need to be industrialised if they should be used on a larger scale. An excellent example of this is the production of the superconducting accelerator modules needed for the XFEL or of the large-scale production of detector elements needed for the LHC. The programme makes an effort to structure relations to industry, to foster intellectual exchange, and to generally find new areas of cooperation and collaboration.

Both accelerator and detector R&D have been recognised around the world as central for the success of science in this area. In numerous road maps formulated in all regions of the world the need for a focussed and prioritised research programme in accelerator and detector science is stressed.

1.1.1 Research Topic “Accelerator Research and Development”

Accelerators are the basis for much of the science done within the research field “Matter”. They serve a broad range of scientific, medical and industrial applications. Accelerators continue to be central tools for the fundamental research into the structure of matter, as exemplified by the LHC accelerator at CERN, are used in a wide range of material research from nano-materials to biological substances, and find applications in medical facilities or material processing in industry. The development of accelerator technology therefore is an engine that powers developments in technology and innovation.

Via the research field “Matter”, the Helmholtz Association wants to strategically position itself internationally in a central place in the development of novel accelerator technologies. The advancements in accelerator based science need even more powerful accelerators – be it with higher acceleration gradients, as needed in particle physics, or be it for much increased intensities and shorter beam pulses, as needed by experiments with photon beams. Science as well as future applications would also greatly benefit from breakthroughs in accelerator technology, to be able to build compact, affordable, and reliable facilities.

The programme topic ARD thus has been designed to develop key competence and technologies in the following four areas (subtopics):

- Superconducting RF Science and Technology
- Concepts and Technologies for Hadron Accelerators
- Picosecond and Femtosecond Electron and Photon Beams
- Novel Acceleration Concepts

ARD draws from a large body of experience in the participating Helmholtz Centres and partners. The available infrastructures, the accelerators, and the collected expertise from accelerator scientists and engineers form excellent conditions for a high quality, innovative research programme. The topic complements and exceeds the work in accelerator science that is on-going in the context of the two other programmes in the research field “Matter”. It will provide the opportunity to develop and advance technologies that answer to the needs of future accelerator based user facilities. It will develop large synergies by bringing together the different Helmholtz Centres, other research institutions, universities and industry, and by sharing resources and facilities.

The topic is based on the portfolio topic ARD, which was initiated within the context of the previous funding cycle by the Helmholtz Association. This topic, while smaller in scope and financial volume than the topic now proposed, served as a framework in which coherent activities in this field were started. The project received additional funding of 16.7 Mio EUR for the years 2011-2014 from the Helmholtz Association.

1.1.2 Research Topic “Detector Technology and Systems”

Particle and radiation detectors with excellent spatial, time, and energy resolution are essential tools to utilise the scientific potential of the large infrastructures available within the research field “Matter”. Experiments in “Matter” are designed to investigate the most fundamental questions in nature, to investigate matter in extreme detail and study the way matter evolves in time and space. The detectors needed for this become more and more sophisticated, providing more detailed views of the reactions and on the details of the structures under investigation. Novel technologies are needed to meet the demands. This requires both, research in new technological areas, and the utilisation of industrial developments available for example from consumer electronics applications. The need of ever increasing details requires that smaller and smaller structures are required to record the events. Miniaturisation and extreme feature density are key challenges that need to be mastered.

To record pictures at optimal resolution at the upcoming European XFEL free electron laser, built currently at the Helmholtz centre DESY, will require pixelated detectors that cover large areas without dead zones, and which allow rapid readout and data transfer. New, highly integrated, three dimensional solid-state detectors need to be developed for this. The upgrade of the largest accelerator in the world, the LHC, which is scheduled to take place during the second half of this decade, will require large area efficient and fast particle detectors. Future facilities like FAIR, under construction at the Helmholtz centre GSI, or a possible future linear collider will need these and other technologies like gaseous detectors for their experimental programmes. Developing such technologies not only enables experiments at the frontiers of science but also provides spin-offs into applications outside of science. Medical imaging is an example often quoted, which profits greatly for example from the development of efficient photon imaging detectors, e.g. to improve positron emission tomography.

The topic “Detector Technology and Systems”, the second topic of the new programme “Matter and Technology”, will utilise the expertise and know-how from five Helmholtz Centres in the research field “Matter”, and formulate a coherent and focussed research plan. It is constructed along three strategic elements (subtopics):

- Sensors, ASICs and Interconnects
- Data Transmission and Processing
- Detector Systems.

The first two subtopics aim at developing technologies needed to construct the advanced detectors necessary for current and future research in the field “Matter”. A strong focus is on the development of semi-conductor based detectors, but other options are explored as well. The development of fast readout schemes, in particular fast high bandwidth links, and of appropriate algorithms to process the data are the subject of the second subtopic. Within the third subtopic the technologies developed in the other two subtopics are combined and integrated into systems. These systems demonstrate that the technologies are not only of academic interest, but are also applicable and usable for actual detectors.

The detector research topic is embedded in a network of national and international partners. The German research structures like “HICforFAIR”, or the Helmholtz Alliance “Physics at the Terascale”, are used to ensure a seamless and close connection to the university community in Germany. Key partners from around the world form the backbone of a technology network to gain access to the most advanced and ambitious technologies available.

Within the Helmholtz centres participating in this subtopic a large body of expertise exists which forms the basis for the work. Through the restructuring and focussing of activities in one subtopic, synergies will be realised among the centres, which will strengthen the field more than any centre could do individually.

Similar to the accelerator topic the detector technology platform was started as a project in the previous funding period, and received a start-up funding of 7 Mio EUR for the years 2012-2014.

1.2 Research Environment

Germany spends annually about 75.5 billion Euros (2011 data, source “Statistisches Bundesamt) on research, distributed in a 70:16:14 ratio between industry, universities and research institutions (Helmholtz Association, Max Planck Society, Fraunhofer Gesellschaft, Leibniz Gemeinschaft and others). Of these research institutions, the Helmholz Association with its annual budget of about 3.4 billion Euros (2011 data) is the largest. It focuses on the grand challenges facing today's society. Its prime missions is the operation of large-scale facilities for research in the natural sciences. These numbers illustrate the important and central role large scale publicly funded research plays in Germany.

The research field “Matter” in the Helmholtz Association operates in a highly international environment. This is maybe most explicit in the area of particle physics, where at the moment only one facility exists on the world at the frontier of highest energy collisions, the large hadron collider at CERN. With the FAIR and the European XFEL facility unique research infrastructures are being built in Germany that will dominate the field of hadron physics and research at free electron lasers for many years to come. With PETRA III, BESSY II, ELBE, ANKA, etc smaller but unique infrastructures are operated within the research field. These large infrastructures are all developed in concert with international strategies to explore the natural sciences. The European XFEL will be the most powerful of the existing or planned free electron lasers around the world. It addresses key questions in matter ranging from material science to structural biology. The Helmholtz Association is a key partner in the international consortium building this facility. Thus, the technologies needed at the XFEL, both for the accelerator and the detectors, are of key interest to the association. The FAIR facility will substantially enhance the possibilities for fundamental and applied science in heavy ion and anti-proton physics in Germany. Again, the Helmholtz Association is a key partner for the construction, and thus takes a keen interest in the technologies required for this facility. The LHC at CERN - even though not based in Germany - is financed with significant German contributions, and has a strong participation from the Helmholtz Association. It will be the prime facility for research at smallest scales and highest energies for the next decade at least. Altogether, the different major facilities are well embedded into the national and international research roadmaps.

Fundamental detector and accelerator science traditionally has a strong base at universities, in addition to the research centres. Especially universities in Germany have achieved a great international recognition as centres of excellence in these areas. They have successfully instrumented for example the initial version of the LHC experiments, or the detectors at FLASH or PETRA III, BESSY II, ANKA, ELBE and other facilities. With the new programme “Matter and Technology” the Helmholtz Association wants to support this development by extending the expertise and know-how base at the centres. Instrumentation and accelerator research increasingly requires access to facilities and tools which are beyond the capabilities of a single university or laboratory. By following a common strategy, and by closely collaborating, the Helmholtz Centres through this programme contribute to a national strategy to maintain and develop excellent international expertise in both accelerator and detector science.

Though the new programme does not operate large infrastructures for users on its own (LKII facilities in the Helmholtz structure), its goals and scientific questions are driven by the many world-class infrastructures available to research in Germany through the Helmholtz Association. In many cases the people contributing to the technological R&D do contribute as well to the construction, operation and scientific utilization of these infrastructures, ensuring that a close connection exists between development and operation.

Members of the programme are actively and successfully participating and involved in the acquisition of third party funded project like TIARA, EUREKA, AIDA, EUCARDII, to mention only a few. In many instances people from Helmholtz Centres have leading roles in these intiatives, or were instrumental in the proposal and execution phase.

The Helmholtz centres participating in this programme pursue an active policy towards technology transfer. As elaborated in more detail in the second volume of this proposal all centres operate dedicated technology transfer departments, which work closely with the scientific groups to identify results suited for a broader application, and support the transfer process.

1.3 Profiles of the Participating Centres

1.3.1 DESY

DESY is a leading centre for accelerator research and development and for the exploration of the structure of matter. It is located on two sites, in Hamburg and Zeuthen. DESY has a focused research programme in accelerator development, photon science and particle and astroparticle physics and is thus well represented in all programmes within the research field Matter. DESY has long experience in the construction and operation of large-scale research facilities like HERA, PETRA or the X-ray laser FLASH. The laboratory also hosts the European X-ray Free Electron Laser (European XFEL). DESY is a key partner in many international projects such as the LHC or IceCube and has been a central player in the preparatory work towards the next large scale facility of particle physics, a linear collider. Driven by the resulting needs, DESY is contributing and driving advanced developments for accelerator and detector technologies, and is thus a major contributor to the programme “Matter and Technologies”. DESY attracts more than 3000 scientists from over 40 countries annually using the DESY infrastructure.

1.3.2 FZJ

Forschungszentrum Jülich (FZJ) is one of Europe's largest interdisciplinary research centres, aiming to identify comprehensive solutions for the grand challenges facing society. Research comprises the fields of health, energy and environment, and information technology with a strong basis in the physical sciences. World-class tools such as supercomputers, analytical equipment, imaging instrumentation and accelerators are employed to generate results with direct benefits for society.

Within the programme Matter and Technology of the Research Field Matter, Jülich exploits its equipment and experience, and takes on a leading role in developing technologies for FAIR, e.g. the construction of HESR and contributions to PANDA. Jülich operates and develops the CoolerSynchrotron COSY and pursues plans for advanced accelerator-based future research infrastructures. In this context, the direct access and close cooperation with the Jülich Supercomputing Center (JSC) and with the Central Institute for Engineering, Electronics and Analytics (ZEA) comprising the divisions Engineering and Technology (ZEA-1) and Electronic Systems (ZEA-2) is an invaluable asset.

1.3.3 GSI

The GSI Helmholtzzentrum für Schwerionenforschung at Darmstadt - with its linear accelerator-synchrotron-storage ring complex UNILAC-SIS18-ESR - belongs to the world-leading research centres for nuclear physics and research with ion beams in other fields. The mission of GSI-DA during PoF-III is the construction and commissioning of the FAIR facility together with the national and international FAIR partners. During PoF-III (2015-2019) GSI-DA has therefore been exempted from the PoF-III-evaluation process. Since 2009, research at GSI within “Matter” has been complemented and considerably strengthened by the foundation of the two Helmholtz-Institutes (HI) Jena and Mainz located as outstations of GSI at the respective campus of the university. As the last stage of their foundation process, both Helmholtz-Institutes will take part in the programme oriented funding of the Helmholtz association. HI Mainz will participate in the programmes “Matter and the Universe” and “Matter and Technology”, and HI Jena in the programmes “From Matter to Materials and Life” and “Matter and Technology”, respectively. In the programme “Matter and Technology”, the Helmholtz-Institutes work together with the GSI centre at Darmstadt, who participates with expertise, manpower and funding – though this GSI-participation coming from GSI’s budget is exempt from the review process.

1.3.4 HZB

The Helmholtz Zentrum Berlin für Materialien und Energie, HZB, operates two large research infrastructures, the neutron source BER II and the synchrotron light source BESSY II. HZB is one of the few centres worldwide to provide and support both neutron and photon sources for energy and materials research. Both facilities serve an international user community, hosting more than 3,000 external users per year. HZB has strong expertise in accelerator research and development of synchrotron radiation methods in the VUV and soft X-ray regime as well as in science-driven design of instruments and precision optics.

The research programmes on structure, dynamics, and function of matter, and on energy conversion & storage combine with in-house expertise and methodical engineering to build and operate state-of-the-art, and in some cases, the world's leading instruments. HZB accelerator research is focusing on development of a new user facility concept for providing variable optimised pulses (BESSY^{VSR}), and on building the prototype energy-recovery linear accelerator BERLinPro to study the feasibility of an ERL-driven multi-user light source. Both activities are important milestones on the roadmap for a successor to BESSY II.

Energy research at HZB focuses on renewable energies, and specifically on photovoltaics and solar fuels, covering these whole fields, from fundamentals to materials and devices. HZB has established the PVcomB centre to support the transfer of knowledge and technology. HZB also pursues fundamental research in electrochemical energy storage and energy efficiency. The aim is to design new materials, prototypes, and modules, leveraging the unique opportunities for materials and process characterisation at its large scale facilities BER II and BESSY II. A dedicated user service for energy research at BESSY II and a strong position in particular in materials research for photovoltaics and solar fuels will be strengthened further with the establishment of the "Energy Materials In-Situ Laboratory" (EMIL), starting operation in 2015.

1.3.5 HZDR

Originally founded in 1956 the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) was re-organized in 1992 and became a member of the Leibniz Association. As a consequence of the very positive evaluation of the German Science Council in 2008, HZDR became a new member of the Helmholtz Association in 2011. Today, HZDR has eight institutes conducting research in the Helmholtz research fields "Energy", "Health" and "Matter".

In the field of "Matter" HZDR research is based on two pillars. One is the understanding of structure, dynamic and function of matter especially under extreme conditions like very high electromagnetic fields. Here, HZDR also runs its Ion Beam Centre (IBC), Dresden High Magnetic Field Laboratory (HLD) and the ELBE-centre with secondary radiation sources as dedicated user facilities. The other pillar is research and development for accelerator technologies covering superconducting RF technologies, time structure of electron and photon beams in the pico- to femtosecond range and novel high power laser-plasma based acceleration concepts. Moreover, it is devoted to research and development for new detector technologies reaching from basic research to medical applications.

1.3.6 KIT

The Karlsruhe Institute of Technology (KIT) was founded in 2009 by the merger of the former Karlsruhe Research Centre (Forschungszentrum Karlsruhe, FZK) and the former University of Karlsruhe (TH). KIT combines the mission of a state-run university with that of a national research centre in the Helmholtz Association. Its staff of 9400 makes the KIT one of the world's largest research and teaching institutions. KIT's major research fields are: Energy, Climate and Environment, Nano- and Microtechnologies, Elementary Particle and Astroparticle Physics, Mobility Systems, Information and Robotics, Humans and Technology.

Within the research field "Matter" KIT operates the national synchrotron light source ANKA and the Grid Computing Centre Karlsruhe (GridKa). It is presently constructing the accelerator test facility FLUTE. KIT contributes to numerous particle and astroparticle physics experiments including AMS, the Pierre Auger Observatory, Belle II, CMS, CMS Upgrades, EDELWEISS, EURECA and the KATRIN experiment.

KIT's Institute of Experimental Nuclear Physics (IEKP), Institute for Nuclear Physics (IKP), Institute for Data Processing and Electronics (IPE), Institute for Photon Science and Synchrotron Radiation (IPS) and the Laboratory for Applications of Synchrotron Radiation (LAS) have contributed over decades to the design and construction of cutting-edge detectors and accelerators. Particular assets of KIT are its numerous technical facilities and the technological expertise of the Faculties of Electrical Engineering and Information Technology, Mechanical Engineering, Informatics and Physics.

1.4 Contribution to Cross-programme Activities and Initiatives

The programme MT participates in the cross programme initiative (CPI) “Large Scale Data Management and Analysis” (LSDMA), the cross programme activities (CPA) “Data Management at Large Scale Infrastructures” and cooperates closely with the research field health.

1.4.1 CPI: Large Scale Data Management and Analysis (LSDMA)

The objective of the cross-programme initiative LSDMA is to address the challenge of Big Data in science by establishing a network of knowledge. Scientists from application domains, data scientists, PhD researchers, informatics expert as well as practitioners are enabled to exchange methods, algorithms, tools, services, knowledge, or best practices, to coordinate joint research & development efforts or to develop new ideas for future projects and endeavours. Simply put: a research bridge across all Helmholtz research fields and programmes is established concerning data-intensive science.

This research bridge will address the whole data life cycle of scientific data. Handling scientific data starts with the acquisition of raw data, initial analysis, filtering and possible reduction close to the source followed by its ingest in the data management system. It continues with the pre-processing and analysis of derived data to extract new scientific insights and knowledge, which are then published and taught to young students generating new knowledge in society and also new opportunities for industrial uptake. This must be accompanied with the long-term preservation and archival of primary and derived data as supplementary material in publications and for re-use in future research. Besides data life cycle management and data analysis, aspects of metadata, data structures and formats, security, privacy, visualization, federated storage and access as well as generic algorithms and methods must be addressed in all steps of the data life cycle.

The set of researchers participating in this research bridge should in principle not be limited to the Helmholtz Association. The cross-programme initiative can be beneficial for researchers and data scientists from outside Helmholtz to connect to this network of knowledge, empowering the Helmholtz Association to become a motor for Big Data in Germany, Europe and worldwide.

The cross programme initiative spans the PoF-III programmes “Supercomputing & Big Data” and “Biointerfaces in Technology and Medicine” of the research field Key Technologies, the complete research field Matter with the PoF-III programmes “Matter and Universe”, “From Matter to Materials and Life” and “Matter and Technology” and the PoF-III programmes “Storage and Cross-linked Infrastructures” and “Energy Efficiency, Materials and Resources” of the research field Energy. Further associated programmes are “GeoSystems – The Changing Earth” of the research field Earth and Environment and “Fusion” of the research field Energy.

1.4.2 CPA: Data Management at Large Scale Infrastructures

Computing is a key element for all three programmes in the research field ``Matter''. Considering the computing aspects in each of the programmes, easily a large number of common questions are coming up, specifically in the field of data analysis and in connection to the management of large data volumes (``big data''). One example is the large volumes of data from the up-to-date detectors in the programme MML and from the LHC experiments, both being in the range of PetaBytes per year. In order to address the common computing issues across the programme boundaries, the interdisciplinary topic ``Data Management at Large-Scale Infrastructures'' was defined.

The primary goal of this proposal is to combine forces from all relevant fields in ``Matter'', ranging from life science to particle physics, and to share knowledge in this particular research field. With the High Data Rate Initiative (HDRI) initiative in the programme PNI of the second funding period, and the development work in particle physics during the second funding period, a strong basis for these activities was created. This work will be continued with the HDRI in MML, in particle physics and in addition in the new third programme of ``Matter'', MT. An organisational frame will be setup to manage an intensive collaboration. The additional benefit will be in the preparation of joint proposals to funding agencies like the EU within Horizon 2020, the BMBF or others, which all consider the topic ``Big Data'' as very important today.

The activity ``Data Management for Large-Scale Infrastructures'' is coordinated by the DESY IT group. All resources are allocated to the programmes directly. Through this cross-programme topic, ``Matter'' will contribute solutions to and will strongly cooperate with the „cross-programme initiative“ (CPI) LSDMA (Large-Scale Data Management and Analysis) that spans all Helmholtz research fields.

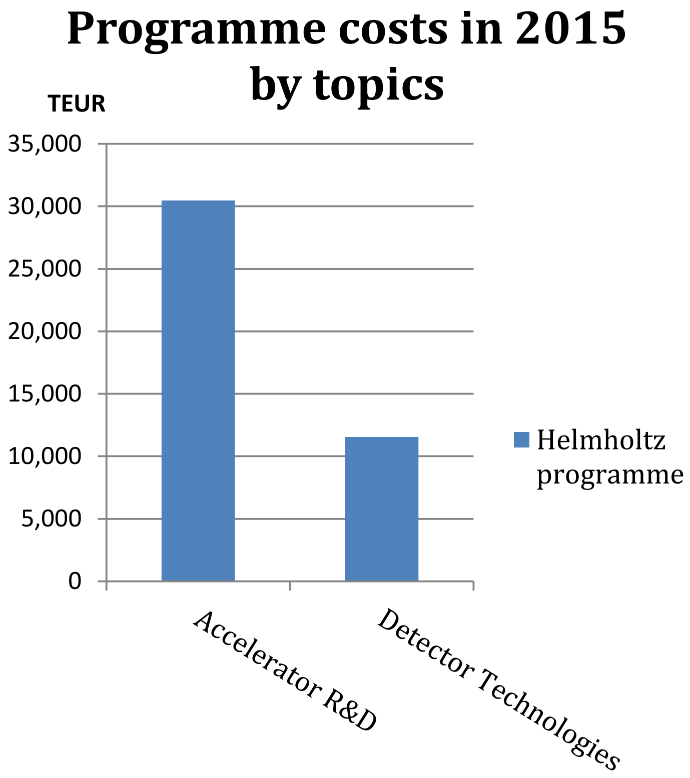
1.4.3 Health

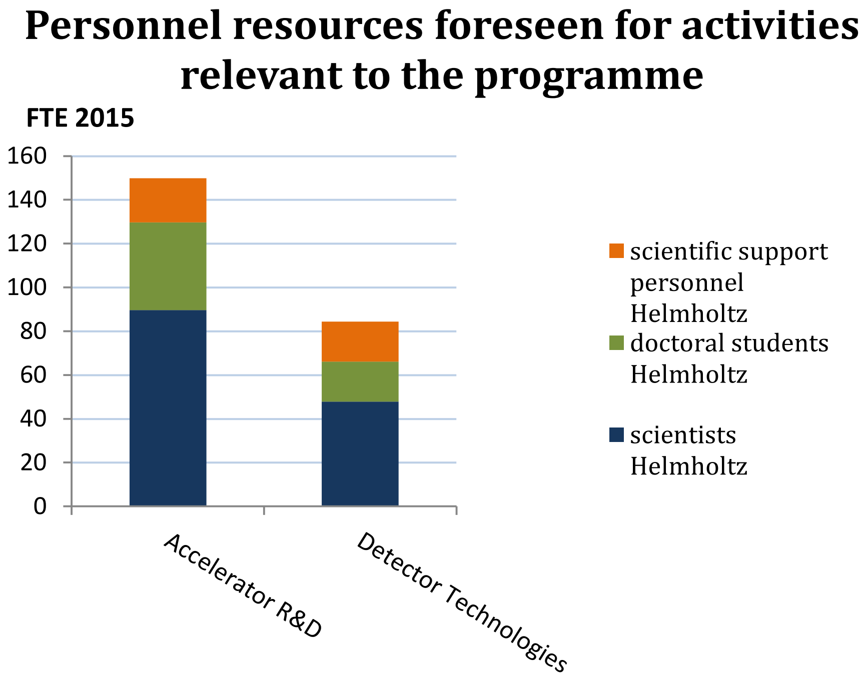
Modern individualized radiation therapy for cancer treatment requires high precision particle beams delivered by cost-effective and compact sources as well as sophisticated systems for the online control of the dose applied according to treatment planning. This combination ensures effective tumour treatment with a minimum of side effects for the patient. Research on and development of advanced technologies for clinical application represents a huge interdisciplinary challenge.

Researchers of the current programme together with scientists of the Helmholtz programme „Cancer Research“ within the research field “Health”, in particular with the topic “Imaging and Radiooncology”, develop novel laser plasma based accelerators, beam delivery concepts and innovative detector systems in order to fulfil this task.

1.5 Planned Resources

The total planned resources for the programme “Matter and Technology” are summarised in the following graph:





2 Programme Development and Organisation

2.1 Development and Environment

2.1.1 Development of the Programme

Accelerator and detector technologies are becoming more and more complex, and face longer and longer development times between the initial proposal and the realisation of a new facility. To remain at the forefront of the technological evolutions requires a constant investment into basic R&D work in these areas, maintaining a pool of excellent people and following a long-term strategic plan. The Helmholtz Association and the participants of the research field “Matter” have reacted to these developments by starting two initiatives during the past funding cycle: the “Accelerator Research and Development” programme (ARD), and the “Detector Technology and Systems” (DTS). Both were initiated in the context of the portfolio process within the association, which made new funds available to research topics that have been recognised to be of strategic importance for the Association and which needed significant strengthening. Based on the very positive experience with these two projects the research field “Matter” decided to form a new programme, based on the portfolio topics ARD and DTS, within PoF-III. The new programme is charged to develop and maintain the technological expertise in these fields, to follow the most up-to-date technological developments, and to prepare the way that these will eventually be useful for the scientific programmes within the research field and beyond.

The Accelerator Research and Development programme, ARD, started in 2011, in the midst of the previous funding period, and has received an extra funding of in total 16.7 Mio EUR until 2014. The detector initiative (DTS) started a year later, and received a total funding of 7 Mio EUR until 2014. Both projects have been developed into topics within the new programme “Matter and Technology”, with a yearly proposed budget of about 31 Mio EUR for ARD, and about 12 Mio EUR for DTS.

2.1.2 Strategic Partners, Cooperation and Competition

The new programme is closely integrated into networks in Germany and beyond. Both topics are very international in nature, and many co-operations and collaborations exist and are developed between the Helmholtz Centres, and German and international partners.

A special role is assigned to German universities as both topics were from the beginning designed and operated in close cooperation between the Helmholtz Centres and the universities.

The new programme focuses on the development of fundamental technologies, and does not primarily serve the immediate needs of single research groups or facilities. However, the programme is very closely integrated with the other two programmes within the research field “Matter”, “Matter and the Universe” and “From Matter to Materials and Life”. The strategic planning and the priorisation of the topics to be investigated are done in close cooperation and coordination of these two programmes. The overarching goal is to develop technologies that are needed and will be applied in one of the many projects pursued within “Matter”. This feedback loop between the developer and the user is essential and a key component of the new programme. The activities in matter and technologies are to a very large extend done in an international context. Most topics are investigated in more or less formal collaborations, involving research centres from Germany and abroad, and universities. A few partners, primarily in Germany, are of key importance for this programme to the extend that they contribute centrally to the success of this enterprise. They are listed in the table.

Participating associate partners

RWTH Aachen	Rheinisch-Westfälische Technische Hochschule Aachen (Germany)
CERN	European Organisation for Nuclear Research, Geneva (Switzerland)
TU-Darmstadt	Technical University Darmstadt
U-Frankfurt	Johann-Wolfgang-Goethe University Frankfurt
U-Hamburg	University of the Freie and Hansestadt Hamburg
FSU-Jena	Friedrich-Schiller-Universität Jena
JLAB	Jefferson Laboratory, Virginia (USA)
JGU-Mainz	Johannes Gutenberg Universität Mainz
HLL MPG	Halbleiterlabor of the Max Planck Gesellschaft, München
PSI	Paul Scherrer Institute, Villingen (Switzerland)
UKD	Universitätsklinikum Carl-Gustav Carus, Dresden, OncoRay

Further German cooperation partners

HU-Berlin	Humboldt Universität zu Berlin
MBI	Max Born Institut, Berlin
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig
TU-Dresden	Technical University Dresden
TU-Dortmund	Technical University of Dortmund
U-Bonn	University of Bonn
U-Gießen	University of Gießen
U-Rostock	University of Rostock
U-Siegen	University of Siegen

Further international cooperation partners

ASG	ASG Superconductors S.p.A, Genova (Italy)
BINP	Budker Inst. for Nuclear Physics, Novosibirsk (Russia)
BNL	Brookhaven National Lab., Upton N.Y. (USA)
Cornell	Cornell University, Ithaca, NY (USA)
Daresbury	STFC-Daresbury Lab. (UK)
FNAL	Fermi National Accelerator Lab., Batavia ILL (USA)
IBS/RISP	Inst. for Basic Science/Rare Isotope Science Project (Korea)
IMP-CAS	Inst. of Modern Physics, Chinese Academy of Sciences (China)
INR	Inst. for Nuclear Research, Troitsk (Russia)
INFN	National Inst. for Nuclear Physics (Italy)
KVI	Kernfysisch Versneller Instituut, Groningen, The Netherlands
KEK	KEK High Energy Accelerator Research Organisation, Tsukuba (Japan)
LBNL	Lawrence Berkeley National Lab. (USA)

MiSU	Michigan State University, East Lansing MI (USA)
MoSU	Moscow State University (Russia)
NCBJ	National Centre for Nuclear Research, Swierk (Poland)
RIKEN	RIKEN (Japan)
SLAC	SLAC National Accelerator Lab., Menlo Park (USA)
StPSU	St. Petersburg State Polytechnical University (Russia)
TRIUMF	National Centre for Nuclear and Particle Research, Vancouver (Canada)
TU-Lodz	Department of Microelectronics and computer science, Technical University of Lodz (Poland)
TU-Warsaw	Warsaw University of Technology (Poland)
UCLA	University of California, Los Angeles, CA (USA)

On the national scale three Helmholtz Alliances play an important role in channelling the close cooperation with universities in the field. The Helmholtz Association and universities have designed a platform for exchange on a – mostly – national basis, and the definition of common projects, and on common training and education programmes. With the new programme structure the three alliances which were all initiated during the second funding cycle will be integrated into a network in matter, MuTLink, which will coordinate some central activities, increase the interchange among the partners, and provide a national communication platform between universities and Helmholtz centres.

A particular speciality of the detector topic is that most partners are embedded into international collaborations to actually build detectors. Such consortia are for example in charge of the detectors at the XFEL or at FAIR and built the large detectors at the LHC. The activities therefore are done in a matrix structure where the partners from the different detector projects, the different Helmholtz partners, and the university partners are all involved. The number of partners which are relevant for the programme are given in the performance indicators.

2.1.2.1 Short Profile of the associate programme partners

RWTH Aachen

A strong partnership between RWTH Aachen University and FZJ is established by JARA - Jülich-Aachen Research Alliance. In this well-established scientific environment, which includes joint training of students and PhD programmes, the research field JARA-FAME (Forces and Matter Experiments) focuses on basic physical research in the field of nuclear and particle physics, and aims to investigate and improve our understanding of matter-antimatter asymmetry in the universe. Regarding the ARD activities, besides the Physics Institute the Institutes for High Voltage and for High Frequency of RWTH Aachen are strongly involved in the programme.

CERN

The European Organisation for Nuclear Research CERN holds a long-standing internationally acknowledged top ranking in the field of accelerator research and development, ranging from theoretical particle dynamics and associated simulation tools to novel accelerator and magnet technologies, machine control and protection systems as well as diagnostic instrumentation. CERN's efforts in these fields are highly interlinked with the according national research programmes of its European member states, particularly also with the Helmholtz activities within the programme "Matter and Technology". A strategic partnership with KIT exists in several key fields of accelerator R&D. Building on KIT's expertise in superconducting insertion devices, a prototype damping wiggler for the compact linear collider (CLIC) will be installed and tested at ANKA. Another cooperation involves the development of novel, plasma-based acceleration technologies. Furthermore, KIT serves as host institute for several Wolfgang-Gentner Scholarships, a programme to train PhD students from German universities in an international, world-class high-tech environment.

Technical University Darmstadt

The Technical University of Darmstadt (TUD) is one of GSIs strategic partner universities. The TUD and GSI offer common training and education for students of engineering and natural sciences. Several chairs in the physics and engineering faculties are occupied by GSI employees. The TUD provides support in the development of several accelerator subsystems. The TUD nuclear physics department participates in the field of dynamic vacuum by providing the academic frame for doctoral students and by a funding support for the required equipment from the German research network grant “Verbundforschungsprogramme”.

In the last years, it supported both experimentally and theoretically the LIGHT collaboration within the ARD programme. In particular, the Institute for Nuclear Physics is leading the LIGHT collaboration and is providing most of the targets specific to the programme.

Johann-Wolfgang-Goethe University Frankfurt

The institute for applied physics (IAP) Frankfurt has a long tradition in the development and operation of accelerator facilities. The institute has a world-wide leading position in the design and production of advanced normal- and superconducting linac structures and is one of GSIs strategic partners. The IAP hosts a number of chairs in physics, which are partly occupied by department leaders of GSI. Common lectures and grants are offered for students. The IAP supports the development of a full performance superconducting linear accelerator module as well as the activities of GSI in fundamental studies of the dynamic vacuum in circular accelerators and provides the academic frame for master and doctoral thesis in this field.

For the LIGHT collaboration, the JWG University provides extensive support in simulation for the coupling of laser-accelerated ions into conventional structures.

Hamburg University

The University of the Freie and Hansestadt Hamburg and DESY have a history of strong cooperation over several decades. Close ties exist in particle, condensed matter and accelerator physics. DESY and part of the institutes of the U-Hamburg Physics department are placed on the same campus and share research infrastructure (like CFEL). The close cooperation is underlined by the strategic *Partnership for Innovation, Education and Research* (PIER). Within PIER, accelerator physics and technology is a field of competence (recently named *Voss-Wideröe Centre for Accelerators*). With about 10 FTE scientific personnel (including three full professors for accelerator physics) and some 20 PhD students, U-Hamburg makes a very visible and crucial contribution to the ARD activities. Groups from the experimental particle physics group participate centrally in the detector development activities, in particular in the area of readiation hard silicon.

Friedrich-Schiller-Universität Jena

Friedrich Schiller University Jena is an internationally renowned centre of laser physics and technology. Outstanding examples are the development and operation of diode-pumped PW-class laser systems and high-power fibre lasers. Furthermore, FSU Jena has a well-received expertise in laser-particle acceleration, attosecond laser physics, and strong-field QED. In addition, the university has a highly visible group working in X-ray optics and spectroscopy. Another field of competence relevant to this proposal is super-conducting and semiconductor detector development. With about 30 FTE scientific personnel involved into the research activities of the HI Jena (including five chairs in experimental and theoretical physics), FSU-

Jena is a strong partner for research in the programmes “Matter and Technology” and “From Matter to Materials and Life”.

Jefferson Accelerator Laboratory

JLab Accelerator Laboratory in Newport News/ VA, US is a world-wide leader with special expertise in superconducting accelerator technology in particular development and production of Niobium cavities for electron accelerators. JLab operates superconducting accelerators for nuclear physics and FEL applications. There is a strategic partnership with HZDR for the development of cavities for superconducting RF photo sources as well as for advanced beam diagnostics at high-current electron accelerators and THz generation.

Johannes Gutenberg-Universität Mainz

Johannes Gutenberg-Universität Mainz (JGU) is among the 8 largest universities in Germany with about 37.000 Students (12% international). JGU is operating on the campus two major research infrastructures: the research reactor TRIGA and the 1,6 GeV electron accelerator MAMI which has been identified by OECD in 2008 as one of world-wide 7 important accelerators in the field of nuclear physics. JGU has expertise in the development of large detector systems as well as accelerator science. JGU has created two full professorships in the field of accelerator science and atomic physics complementing the new GSI position in HI Mainz. In addition, JGU and the local state Rhineland- Palatinate are constructing a research building (38 M€) for housing the HI Mainz staff which receives in addition national funding from the German "Wissenschaftsrat". The laboratory space of the HI Mainz-Building includes an experimental hall with pilot plants for superconducting cavities, electron cooler magnets and a clean room for the mounting of superconductive cavities for which the operating costs will in part be carried by JGU. JGU hosts the excellence cluster PRISMA which has been granted in the second German excellence initiative. HI Mainz is one of four institutes forming the excellence cluster PRISMA. The existing expertise at JGU together with the newly constructed infrastructure for the HI Mainz in the area of detector development and accelerator science and technology render JGU a strong strategic partner in MT.

Halbleiterlabor MPG München

The semiconductor laboratory (‘Halbleiterlabor’) was founded about 20 years ago as a common project of the Max Planck Institute for Physics and the Max Planck Institute for Extraterrestrial Physics. Its main purpose was to develop and produce advanced silicon radiation detectors for the experiments carried out by these institutes. Since 2013 the laboratory is an independent central unit of the Max Planck Society open to all its institutes and also to 3rd parties. The laboratory, which is located in the Siemens Campus in Neuperlach (Munich), operates a 800 m² clean room of up to class 1 with a complete production line for processing 6” silicon wafers (ion implantation, photolithography, chemical etching, LPCVD, metal sputtering etc.) Thus the laboratory offers the unique possibility to design and fabricate advanced silicon detectors optimally matched to the experimental requirements. The range of detectors produced in the lab includes strip and pixel sensors, fully depleted CCDs, active pixel sensors and silicon photomultipliers. They find applications in particle tracking, X-ray spectroscopy and imaging in particle physics, astronomy and photon science.

Paul Scherrer Institut

The Paul Scherrer Institute, Villingen (Switzerland) (PSI) is the largest research centre for natural and engineering sciences within Switzerland and hosts the third generation synchrotron Swiss Light Source (SLS) to conduct research in material sciences as well as SwissFEL, a hard X-ray free electron laser user facility, presently under construction. The strong strategic partnership between PSI and KIT is motivated by the common interest in THz source development, in the study of ultra-short electron bunches, and the development and testing of advanced beam diagnostics. A recent achievement in this context is the worldwide first implementation of an electro-optical bunch length diagnostic system in a storage ring at ANKA.

Other examples are the SwissFEL Test Injector Facility at PSI and the FLUTE accelerator test facility, under construction at KIT with substantial contributions from PSI. Within the programme "Matter and Technology" the FLUTE collaboration will focus on the development and testing of fs-beam diagnostics

Uniklinikum Carl Gustav Carus Dresden (OncoRay)

The University Clinic Dresden (UCD) is an important partner of HZDR on the field of research for cancer therapy. Together with the "Technische Universität Dresden" (TUD) they jointly operate OncoRay, the National Centre for Radiation Research in Oncology Dresden. OncoRay operates a recently implemented clinical proton cyclotron with a unique research infrastructure for the development of medical imaging techniques and translational research with alternative particle sources. Therefore, UCD represents HZDR's central strategic partner for the development of laser ion acceleration techniques as well as for advanced imaging detector development, especially for medical applications.

2.2 Infrastructure

2.2.1 Existing Infrastructures

The centres participating in the programme "Matter and Technology" have all been involved in the relevant research since many years. Extensive and up-to-date laboratory space needed is available at all partners. All centres provide the needed infrastructure for the design and construction of prototype equipment including mechanical workshop, electrical and electronics workshops, and assembly buildings. A number of medium to large scale infrastructures are of special importance for the programme, and are separately listed in the following table.

Centre	**Infrastructure**		**Short Description**
DESY	FLASH	ARD	Test of seeding concepts, additional extraction line from FLASH-2 beam line for PWFA experiments; operation in parallel with FLASH user operation
	PITZ	ARD	Photoinjector test facility; ps ultra-low emittance bunches, modulated bunches for PWFA experiments; versatile diagnostics beam line
	DESY Testbeam Facility	DTS	Testbeam Facility at the DESY-II synchrotron aimed at detector development; three beamlines provide electrons between 1-6 GeV/c and a particle rate up to 1 kHz/cm^2; additional infrastructure such as a large-bore 1 T solenoidal magnet and silicon pixel-based beam telescopes
FZJ	COSY	ARD	Cooler and storage ring that can provide phase-space cooled polarized proton and deuteron beams with momenta up to 3.7 GeV/c; primarily used in accelerator and detector tests to prepare devices and methods in particular for FAIR
GSI	UNILAC/ SIS18/ ESR HLI	ARD	Accelerator complex, Linear accelerator (UNILAC) for all elements up to 11 MeV/m(from p to U^{28+}, also laser accelerated p injection); by injection into synchrotron (SIS18) and storage ring (ESR) ions up to 0,5 GeV/u are available; high intense heavy ions with high duty factor by using high charge state

Centre	Infrastructure		Short Description
			injector (HLI) based on a novel ECR ion source
	Heavy Ion Micro Beam Facility	DTS	Micro beam facility at an UNILAC beamline that allows to aim and hit with individual heavy ions of the 1 to 10 MeV/u energy range with sub micrometer precision; used for the characterization of pixel detectors as well as for electronics radiation hardening
	Detector laboratory	DTS	In view of the future facility FAIR, GSI has erected a new detector laboratory, comprising 600 square meters of high quality clean-room working space, dedicated to gaseous as well as silicon and diamond detector technologies
HI Mainz/ JGU	MAMI	ARD	1.6 GeV electron accelerator used for the exploration of nuclear, hadron and particle physics and applied physics operated by JGU in Mainz
HI Jena	PHELIX	ARD	Petawatt High-Energy Laser for Heavy-Ion Experiments with Petawatt class pulse power in 500fs and improved pulse contrast; 100TW experimental area for ion acceleration with ion beam transport instrumentation
	POLARIS	ARD	Fully-diode pumped laser prototype representing a unique architecture presently delivering 40 TW pulses of up to 6 J in 150 fs at 1/40 Hz with upgrade path to 250 TW and 1 Hz repetition rate. Infrastructure for laser plasma experiments
	JETI200	ARD	250 TW Ti:Sapphire laser system with state-of-the-art pulse contrast, stability, and control. Synchronized to HIJ experimental facilities
	CRYRING	ARD	Dedicated low energy storage ring for highly charged ions, currently getting installed at GSI; can be operated coupled to the ESR or in a stand-alone mode; will be mainly used for atomic physics experiments and will in addition serve as a FAIR test facility
HZB	BESSY II	ARD	1.7 GeV 3rd generation EUV soft X-ray light source; studies and development of new schemes for advanced longitudinal phase space manipulations (e.g. BESSY VSR)
	HoBiCaT	ARD	Horizontal bi-cavity test facility for development of cw srf-systems
	Metrology Light Source (MLS)	ARD	630 MeV dedicated UV/VUV light source (owned by PTB); optimized for low-alpha operation; CSR and THz generation and diagnostics; longitudinal phase space manipulation schemes

Centre	Infrastructure		Short Description
	GunLab	ARD	Photoinjector test facility for high brightness, high current electron beams (under construction, first beam 2015)
	B*ERL*inPro	ARD	Berlin Energy Recovery Linac Project; test facility for the demonstration of low emittance high current energy recovery in a fully sc accelerator setup (under construction, first beam 2017)
HZDR	ELBE Centre Radiation Source	ARD/ DTS	Electron beam driven secondary radiation source (IR and THz with pump-probe capability, Bremsstrahlung, neutrons, positrons); superconducting RF accelerator 40 MeV, 1.6 mA, CW; superconducting RF photo source with versatile test stand, detector test beam
	Elbe Centre High Power Lasers	ARD	Dual beam ultra-short pulse high contrast Ti:Sapphire laser system Draco (Petawatt power, up to 30 J in 30 fs) with dedicated plasma accelerator infrastructure and metrology; synchronization to ELBE; independent second generation energy efficient diode laser pumped Petawatt laser development (Penelope)
KIT	ANKA	ARD	Synchrotron used as test facility for fast detectors with high data throughput and high repetition rates; studies of short-bunch beam dynamics and control in storage rings
	FLUTE	ARD	Test facility for generation of intense sub-picosecond electromagnetic pulses
	Irradiation Centre Karlsruhe	DTS	Proton irradiation facility at the local 25 MeV cyclotron, providing a high flux of about 2.5E13 protons/(s·cm²) to users

2.2.2 Planned Infrastructures

The following infrastructures are anticipated by the programme:

Large investment (> € 2,5 million) proposals planned in the programme period

Individual investment project planned	Centres	Planned investment
SINBAD	DESY	4 M€
PICCOLO	KIT	4.2 M€
Distributed ARD Test Facility	DESY, FZJ, GSI, HZB, HZDR, KIT	40 M€

SINBAD (Short Innovative Bunches and Accelerators at DORIS)

Sinbad is a proposal for a test facility at DESY for research in the ARD subtopics 3 and 4, exploiting to a large extent the synergies between these two areas. It will make use of buildings and available technical infrastructure of the former storage ring DORIS. The scientific programme reaches from the generation of sub-femtosecond electron bunches to multi-stage plasma-wakefield acceleration as a stable, industrial-style accelerator unit. SINBAD also is a step on the way towards DESY's participation in a Distributed ARD Test Facility.

PICCOLO

PICCOLO is a planned upgrade of FLUTE that will provide the necessary stabilization and control to create ultra-short pulses (down to one femtosecond) with high shot-to-shot reproducibility. It will push the frontier of R&D for synchronization and timing systems, and will produce important input for the research on novel accelerator concepts (e.g., SINDBAD at DESY). The controlled generation and shaping of femtosecond THz pulses with PICCOLO, combined with new developments in ultra-fast THz detectors, will offer the opportunity for new experiments in a variety of fields, including in life sciences and medical applications.

Distributed ARD Test Facility

The proposal to build up a distributed ARD test facility is supported by all Helmholtz ARD centres: DESY, GSI with HI-Jena, FZJ, HZB, HZDR and KIT. It includes the linking of present accelerator research infrastructure (collaboration), upgrading of existing facilities for a common usage (synergy) and forming of a few “lighthouse” facilities for internationally leading research towards ultra-compact accelerators and radiation sources (leadership). The involved Helmholtz centers bring in various existing or planned infrastructures: ELBE (HZDR), SINBAD (DESY), JuSPARC (FZJ), test stands for ion acceleration and transport (GSI), center for next-generation high-power laser development (HI-Jena), BERLinPro (HZB) and FLUTE (KIT). The centers will prepare a proposal for strategic investment funding of 40 M€ for the years 2017 – 2020.

2.3 Programme Coordination

2.3.1 Organisation and Cooperation

The programme is organised into two topics, ARD and DTS. Each topic is coordinated by a topic speaker. Each topic itself has structured itself into a number of subtopics.

The coordination team of the new programme consists of a speaker and his deputy, the speakers of the two topics, and their deputies. The coordination teams of the two topics develop and formulate proposals for the research plans for each topic. The central coordination team is responsible for overall strategic issues and common activities. The scientific programme is developed and agreed upon primarily at the level of the programme topic. Through workshop, topical meetings, and discussions among the topic and subtopic coordinators the topic is developed and defined in step with the expectations and capabilities of the participating centres, to best address the scientific challenges. This process is very much based on consensus building among the partners. The scope and definition of the scientific programme is continuously re-visited and adjusted to changing needs and challenges.

The coordination team of the programme is in close contact to the leadership of the other two programmes in “Matter”. Regular strategic discussions take place to determine the most relevant areas of research needed to answer to the technological needs within the research field.

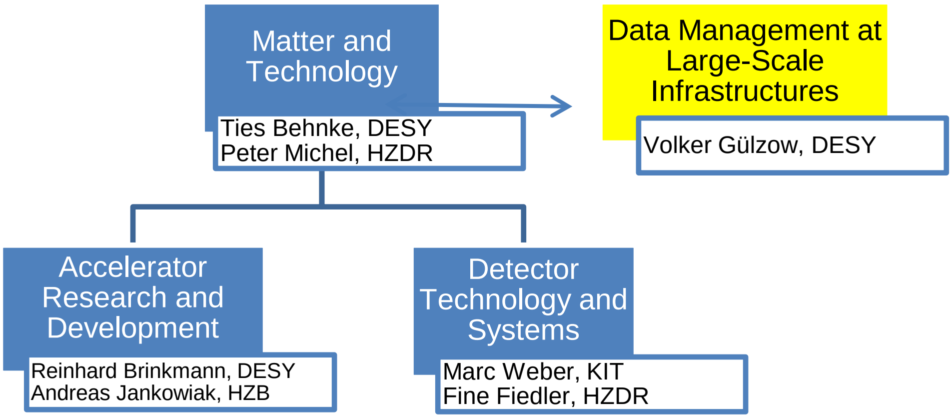


Figure 1: Structure of the programme "Matter and Technology".

There are a number of platforms for information, discussion and decision finding that facilitate this distributed interchange within the research field "Matter".

The Strategy Board is a forum between the directors of Helmholtz centres and the Federal Ministry BMBF which enables direct discussion of significant developments with the political sector. The so-called Dialogue Platform has been established to ensure tight links between the BMBF and a larger representation of the research field "Matter". Its members are responsible decision makers in the Ministry, the Research Field coordinator and the programme spokespersons. The Dialogue Platform meets typically 2-3 times per year. The Steering Committee ("Lenkungsausschuss") of the research field is an internal meeting of the Coordinator, all programme and topic spokespersons and their deputies. It meets four to six times per year to prepare the Dialogue Platform meetings and to conduct in-depth discussions of all matters of the research field Matter.

The programme is embedded in a matrix structure between the management at the participating centres and the programme coordination team. All decisions eventually are taken by the relevant centre managements. The programme coordination team communicates the scientific goals and challenges to the centre management, and works with them on embedding this into the work programme of the centres.

Within each centre procedures are established to review the contributions by the centre both by internal and by external boards. Frequent discussions with the centre will happen to make sure the goals of the programme and the goals of the centre are synchronised.

2.3.2 Planning and Controlling

The structures and mechanisms for the planning and controlling within the programme Matter and Technology are defined by the Helmholtz Association and are largely centred on the contributing Helmholtz centres. In particular, the following elements are foreseen:

- **Reporting:** Helmholtz requires the annual submission of progress reports on the level of the programme (Programmfortschrittsbericht) and on the level of the Helmholtz centres (Zentrumsfortschrittsbericht). On the scientific side, the latter reports are prepared from material provided by topic experts from the centre in question. The programme reports for Matter and the Technology will be coordinated by the programme spokesperson in close collaboration with the topic speakers.
- **Evaluation:** The Helmholtz research programmes are subject to a midterm evaluation process. This review is done at the participating centres

In addition to these formal steps the coordination team of the programme and the coordination teams of the topics review regularly the scientific progress and the budget development, identify problems, and work towards solving them.

2.3.3 Talent Management

Talent management is a central objective of the Helmholtz Association. It encompasses a broad range of measures, from activities to reach young people in the very early stages of education, over the systematic recruitment and development of human resources, to dedicated instruments to improve the gender balance. Each centre has a dedicated strategy to support the career development of personnel at the centres and to maintain a high quality of the staff. The individual centre strategies are described in the extended centre descriptions in volume 2 of this proposal.

The scientific success of “Matter and Technology” relies on the availability of highly qualified people. Education and qualification of scientists and engineers is therefore of key relevance for the programme and the participating centres. Each centre has well defined programs to improve the gender balance in science. They are elaborated in the second volume of this proposal. The programme “Matter and Technology” is dedicated to actively increase the fraction of women in science, and in particular ensure a healthy and adequate representation of women scientists in the leadership of the programme.

In addition to the different actions implemented by the centres the programme “Matter and Technology” has identified a few selected measures which will be implemented on the programme/ topic level. They should serve to support the development of the human resources within the programme and contribute to the coordination of relevant activities among the programme members.

Of particular concern to the centres participating in the programme is the training and education of young researchers. In close cooperation with the centres and universities, students and young engineers are being involved in the programme at different stages of their career. They bring ideas and intellectual power, and are trained on advanced technologies and on collaborative work with international perspectives.

At several centres dedicated efforts are made (Girls day, MINT day, other activities) to interest young female students for science. These efforts complement and expand the gender blind programmes which exit in many centres. These programmes typically reach young girls from 9th grade onwards. They help to lower the thresholds for these girls to later consider a career in a more technical area. It is too early to judge whether these programmes will have a significant impact on the number of incoming female science students, to mention one example, but they are conceived very positively by both the students and their teachers. “Matter and Technology” will actively advance these activities by supporting them at the home centres, but also by exchanging information on successful tools and initiatives among the partners.

To broaden the educational base for students and to support their career development the programme offers specific measures to this group. These measures are meant to supplement the different actions initiated by the centres. In the following a few selected examples are discussed.

Student Exchange

The programme as a whole actively encourages students involved in parts of the programme to spend some time during their training at a different centre. The programme will develop and implement together with the participating centres a scheme to make such exchanges simple and easy to implement. The programme coordination will support students and their supervisors to find an appropriate place for such placements.

Student Mentoring

Students at the graduate level are often scientifically fully integrated into the work of their host centre but lack the experience and standing to plan and systematically develop their career. Most centres offer mentoring schemes to the students, where a student is paired with an experienced researcher who is not involved in the thesis topic. The programme “Matter and Technology” very much encourages such measures, and will support the centres to find suitable matches between mentees and mentors from members of the programme. Such a cross-centre mentoring programme can supplement the local centre based mentoring programmes, and can enter a new element of exchange and interaction among the participating centres.

Young Investigator Groups

The Helmholtz Association and some centres offer the possibility for promising young researchers to start independently funded young investigator groups. Candidates are subjected to a vigorous selection procedure, and the groups are granted on a highly competive basis. The programme “Matter and Technology” will work together with promising candidates and centres and encourage and support cross-centre applications.

Education and Training

Education and training in high technology areas is a key competence the Helmholtz centres offer. Annually all centres together train several hundred doctoral students per year, in all programmes in matter. These people once finished enter into the national and international work force as highly qualified and very much sought after people. Key competences of these people are of course technical, but also sociological – they have learned to operate in an international environment, they can usually communicate very well in at least one foreign language, and they have worked in a highly complex but also very collaborative environment of modern large scale science.

Topical and Interdisciplinary Workshops

The development of cutting edge technology relies not only on excellent people and infrastructure, but also good and intense communication between the different players in the field. The programme will encourage and coordinate a number of key topical and interdisciplinary workshops to further this goal. Already during the PoF-II period a number of events took place.

3 Programme Content

The programme "Matter and Technology" has two topics: Accelerator Research and Development (ARD) and "Detector Technology and Systems" (DTS).

3.1 Accelerator Research and Development

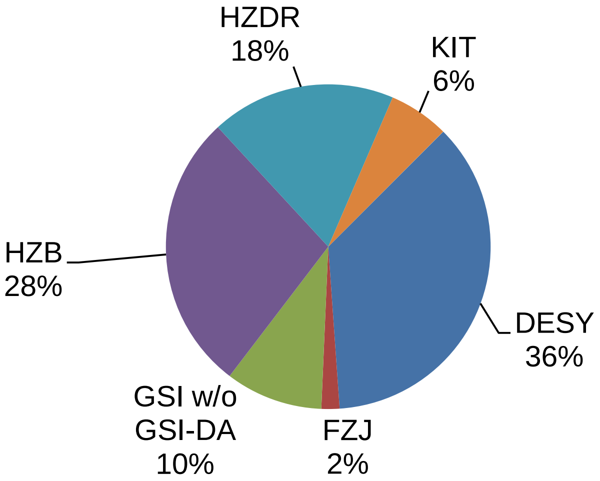


Figure 2: Distribution of resources in the ARD programme topic, according to centre.

The six Helmholtz centres which are involved in the development, construction and operation of accelerator facilities (DESY, GSI, FZJ, HZB, HZDR, KIT) are all participating in the topic Accelerator Research and Development. A breakdown of the proposed contributions to the programme is shown in Figure 2. The topic is based on an initiative launched in 2010 to implement Accelerator Research and Development (ARD) as an own programme topic in the portfolio of the research field Structure of Matter. The ARD proposal was submitted to Helmholtz in December 2010, evaluated by external referees and approved by the Helmholtz Senate in June 2011. A total funding of 16.7M€ was granted for the ARD implementation phase 2011 – 2014.

Research and development in accelerator physics and technology has a long tradition in the centres participating in ARD and was always a prerequisite for the successful research in Helmholtz. Germany has traditionally been one of the leaders in accelerator technology and it is our goal to maintain leadership capabilities and strengthen resources by synergy between the Helmholtz labs and partners in universities and industry. In the past these activities were generally directly related to specific facilities and projects and thus linked to and allocated in the different programmes of PoF-II (and PoF-I). The implementation of ARD and its continuation as an own topic in PoF-III maintains this strong link to other programmes and its impact on the research field Matter. Accelerators are the *enabling technology* for a broad spectrum of research activities. Successful R&D activities will foster improvements and the invention of new concepts for existing accelerator facilities or on-going projects (e.g. ANKA, BESSY II, FAIR and EU-XFEL). This R&D will remain critical for the healthy development of research in Helmholtz. However, the objectives of ARD go beyond this direct impact on the other programmes in Matter. An independent accelerator programme can give dedicated support to generic, future oriented research. This research must also include more high-risk activities with ambitious goals, where a potential for high-impact applications comes together with significant initial technical uncertainties whether "it can be made to work" (e.g. sub-femtosecond beams for ultrafast science applications, ultra-compact plasma-wakefield accelerators). Important benefits for society are possible. For example, the planned ARD programme has links to other research fields (e.g. Health, with compact accelerators for medical treatment and imaging) and to industrial applications (e.g. with XUV radiation sources for nm-scale lithography). Regarding industry, an important impact of ARD is also the transfer of technology and expertise from the research labs, thus advancing the skills and manufacturing capabilities of companies involved in the accelerator business.

A central aspect of ARD and strong driving force for its implementation is the improvement of networking and cooperation between the Helmholtz centres and with Universities participating in the programme. Since the implementation of ARD in mid-2011 a number of workshops have been organized, ranging in their focus from general discussions of the overall strategy and research goals to more specialized meetings on items under investigation in the different subtopics of ARD. Several new ideas for joint projects between Helmholtz labs and universities, common usage of infrastructure and exchange of newly developed technology have already emerged during the first two years of implementation phase.

The creation of the ARD programme had a profound and very positive impact on visibility and international recognition of German accelerator R&D. The visibility of accelerator R&D and its attraction to students at the partner universities has considerably improved. Furthermore, several new co-operations with international partners have already been launched, will be carried out and further extended in the PoF-III period.

The ARD activities are structured into four subtopics (see Figure 3) and will in the following be described according to this structure. Each of these four subtopics represents a highly relevant and future-oriented strategic research field. This groups the well-defined ARD activities in a logical way and helps to organize the joint research work from a practical point of view. However, it does not mean that the subtopics are orthogonal to each other. Rather, there exists a large amount of overlap, synergy and co-operation across the borders of the subtopics. Two examples may illustrate this:

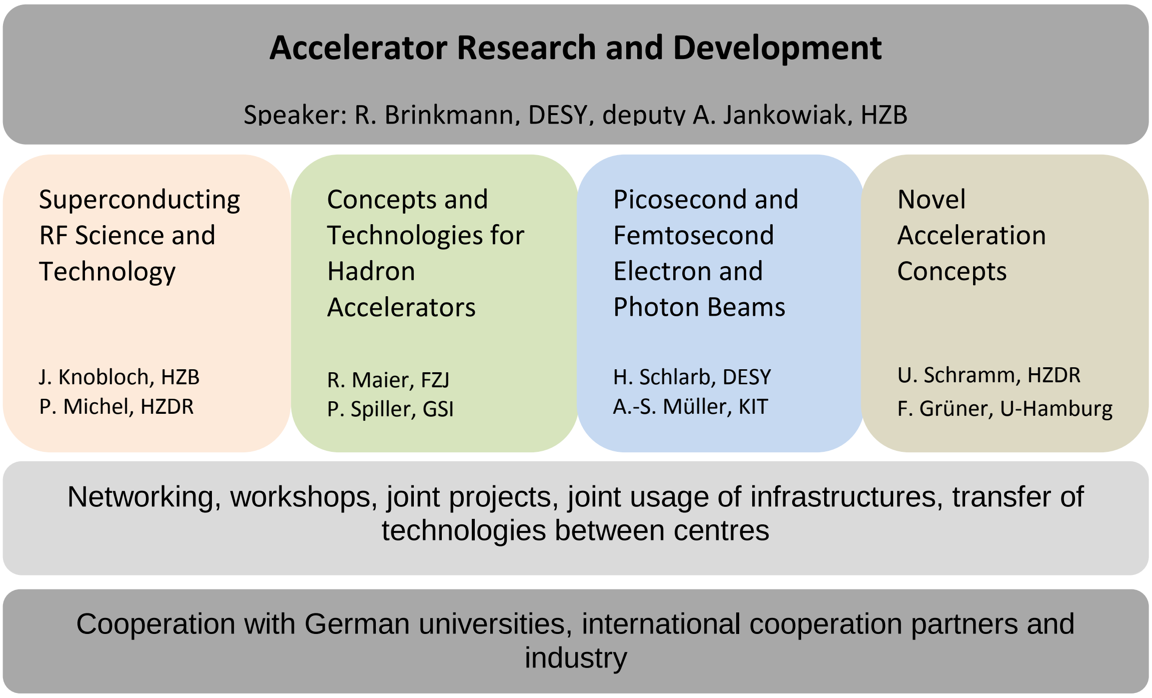


Figure 3: Structure of the ARD research topic

Superconducting accelerating structures, a R&D subject of the subtopic 1, “Superconducting RF Science and Technology” can be employed to push the limits of hadron accelerator concepts (subtopic 2, ST2) as well as provide novel short-pulse capabilities for synchrotron radiation facilities (subtopic 3, ST3)

The objective of subtopic 3, “Picosecond and Femtosecond Electron and Photon Beams” is to push the limits of electron bunch lengths to femtoseconds and below while maintaining an extremely high beam quality. Beams which are produced by plasma-wakefield acceleration (subtopic 4, ST4) aim at very similar parameters. Aspects of beam dynamics and characterization of short bunches can therefore be investigated in full synergy. Furthermore, test set-ups for ultra-short beams can be used to also test injection into plasma wakefields.

The structure and organization of ARD is thus well chosen to foster co-operation, synergies and an efficient joint usage of available resources.

Distributed ARD Test Facility as a Future Research Infrastructure

The Helmholtz ARD programme has led to the development of a coherent strategy and built up of an improved personnel base for accelerator R&D in Germany. The programme sponsors a new type of collaboration in workshops and experiments across all involved Helmholtz centres and universities, as described above. It is the goal of Helmholtz ARD to further strengthen these collaborative aspects and to foster the resulting synergetic effects. For this purpose the “Helmholtz Roadmap for Large Infrastructures” foresees the implementation of a “distributed ARD test facility”.

The proposal to build up a distributed ARD test facility is supported by all Helmholtz ARD labs: DESY, GSI with HI-Jena, FZJ, HZB, HZDR and KIT. Such a facility includes interlinking of present accelerator research infrastructure (collaboration), upgrading of existing facilities for a common usage (synergy) and forming of a few “lighthouse” facilities for internationally leading research towards ultra-compact accelerators and radiation sources (leadership). The involved Helmholtz centres bring in various existing or planned infrastructures: “ELBE centre for high power radiation sources” (HZDR), “SINBAD centre for short innovative bunches and accelerators“ (DESY), “JuSPARC Peta-Watt laser centre for ultra-fast studies and polarized beams“ (FZJ), “test stands for ion acceleration and transport“ (GSI), “centre for next-generation high-power laser development” (HI-Jena), “BERLinPro centre for high brightness CW beams in SC accelerators“ and (HZB) and the “FLUTE facility for THz radiation and short pulses“ (KIT).

A core theme of the proposed investments will be the development of ultra-compact accelerators and radiation sources for science and medicine. This includes R&D up to reaching user readiness and industrial accelerator quality. The Helmholtz centres have the required knowledge and experience to reach such a quantum leap in novel accelerator technology. Many of the ARD subtopics, described on the next pages, directly contribute to the goal of a distributed ARD test facility, which therefore is the logical next step in collaboration. A detailed project proposal for acquiring strategic investment funds is being prepared by the Helmholtz centres and will be submitted for review and approval in 2016. In the current planning the required resources are 40M€ for the years 2017 – 2020.

3.1.1 Superconducting RF Science and Technology

The advancement of accelerator physics over more than six decades has gone hand in hand with the development of radio-frequency (RF) cavities based on copper technology. Due to the large surface resistance of copper, the need to minimise the power dissipation dominates the cavity design criteria. Often these design considerations run contrary to beam dynamics and other operational considerations. Even so, copper cavities must be limited to either low accelerating gradients (e.g., for storage ring facilities) or pulsed operation with a duty factor far below 1%. The dynamic losses in the cavities thus impact and limit significantly the accelerator applications and operating modes.

With the advent of superconducting RF (SRF) technology, the restrictions due to power dissipation are largely eliminated and SRF systems can be optimised both in geometry and operating mode to enable many new and exciting accelerator applications. Such applications rely on SRF to provide high-gradient acceleration for high-average-power and very brilliant beams while minimising the beam disruption on account of their impedance-optimised geometry. In particular, SRF accelerators can often be operated in a very flexible manner, which is proving essential for many new applications.

Given the potential, not surprisingly SRF technology has been very successful in the last 25 years with applications such as CEBAF, SNS, ELBE, FLASH, Soleil, HERA and LHC (just to name a few) proving that routine operation in large-scale facilities is feasible for a broad spectrum of applications. While very successful, these facilities also operate either in pulsed mode (with duty factor in the % range) or at moderate gradient to reduce the required cryogenic cooling. In addition, the average beam current in linac structures is often moderate. Unlike copper technology, though, the limit of SRF technology is far from being reached and a combination of technology development and basic research can make large advances in the field.

3.1.1.1 Challenges

SRF promises to open up completely new options and many exciting applications are now being proposed that otherwise would not be possible. By exploiting SRF's intrinsic capability to provide simultaneously continuous wave (CW) operation at high-gradient acceleration and low losses, these new projects take on a completely new quality that cannot be realised by simply employing "more of the usual" with the present-day technology. It is thus fair to say, that CW SRF systems are the enabling technology. Examples of such systems are CW free electron lasers, x-ray laser oscillators, high-flux Compton gamma-ray sources, ERL-based light sources, ERL-based electron-hadron colliders, THz sources and cavities for short photon pulse operation in storage-ring light sources. Many high-power ion and proton accelerators also rely on CW or long-pulse SRF systems, such as spallation neutron sources, rare-isotope facilities or accelerator driven systems (ADS) for nuclear-waste transmutation and accelerator driven subcritical reactors being developed outside the Helmholtz Association. In all these cases, CW operation offers many attractive, often essential, features, including high-average power with very flexible beam patters, improved stability, smoother data acquisition or the possibility of using highly sensitive detection techniques such as lock-in systems.

The challenge now lies in realising the full potential of SRF, i.e., in advancing its science and technology for CW high-gradient (> 15 MV/m) and high current (> 10 mA) operation while reducing the cryogenic load significantly (at least a factor 2) to reduce the size and complexity of the cryogenic plants. It must be emphasized, that this development requires both technological hardware advances as well as fundamental research to better understand the behavior of existing and new SRF materials in RF fields. The challenge is not limited to the accelerating systems but also includes the generation of appropriate high-brilliance CW beams. Exceeding the capabilities of present-day sources, new applications require an exceptional phase-space density and tailored beams at high average current and with high reliability. Here too, SRF units hold the promise of becoming the next-generation sources that are able to deliver the CW operation at high voltage and gradients required simultaneously to provide high-brilliance beams. Again, both the technology of the injector systems and a better fundamental understanding of photocathodes must be developed to move beyond the current state of the art.

Generic SRF R&F for a broad spectrum of accelerator applications

The overarching theme of ST1 thus is "**pushing the limits of CW-SRF systems**." Many new issues that may be of secondary concern in pulsed machines move into the foreground in CW SRF application, such as cryogenic load, beam impedance, and electron field emission. Resolving these issues will enable a whole new class of accelerators (both large-scale facilities and compact accelerators).

In Figure 4, the R&D programme in ST1 is shown which addresses the requirements of projects within this and other subtopics of ARD (e.g., development of short-pulse electron linac applications & short-pulse storage-ring operation (BESSY^{VSR}) in ST3 and H-type cavities for CW ion linacs @ GSI in ST2) that span the period up to at least 2019. The ST1 programme is intentionally designed to be sufficiently generic for it to be relevant to projects that lie outside the scope of ARD, some of which are being explored by involved Helmholtz Centres, Helmholtz Institutes and Universities (e.g., the conversion of FLASH to a CW FEL or the construction of the CW SRF Mainz Energy-Recovering Superconducting Accelerator MESA). Thus, as shown in Figure 5, ST1 encompasses a significant synergetic component not tied to a specific project. ST1 can react rapidly to changing demands of accelerator concepts being developed within and outside ARD. Its reach also includes technology transfer to industry. Current activities include, e.g., the joint development of CW RF sources for linacs, as recently discussed at an ARD workshop hosted by HZDR[1]. In the longer term, even concepts for both small and medium-scale turnkey CW applications are being explored, such as accelerator-driven light sources for industrialized EUV lithography, as being pursued by Carl Zeiss SMT.

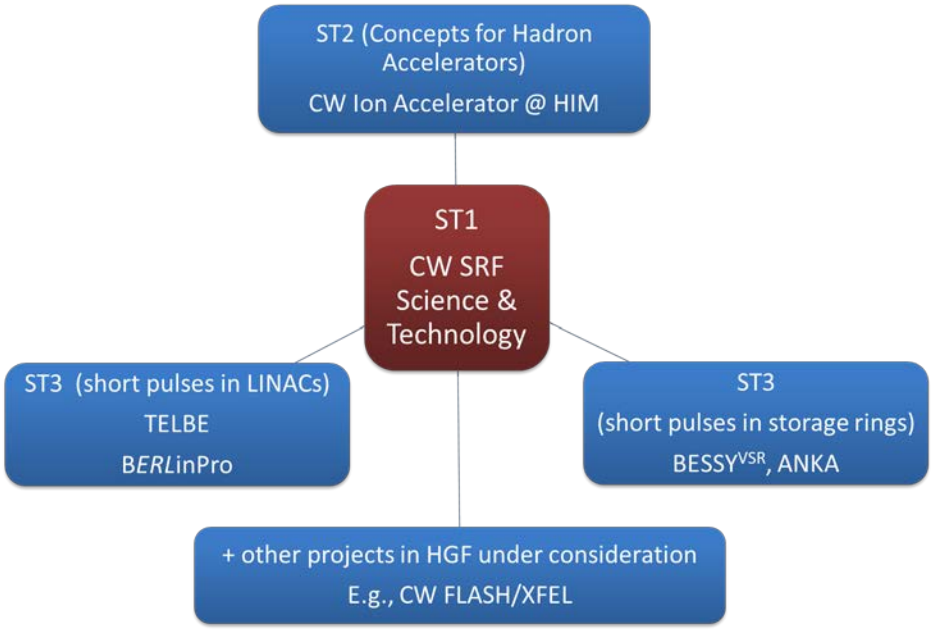


Figure 4: Connection between ST1 R&D and projects in other ARD subtopics

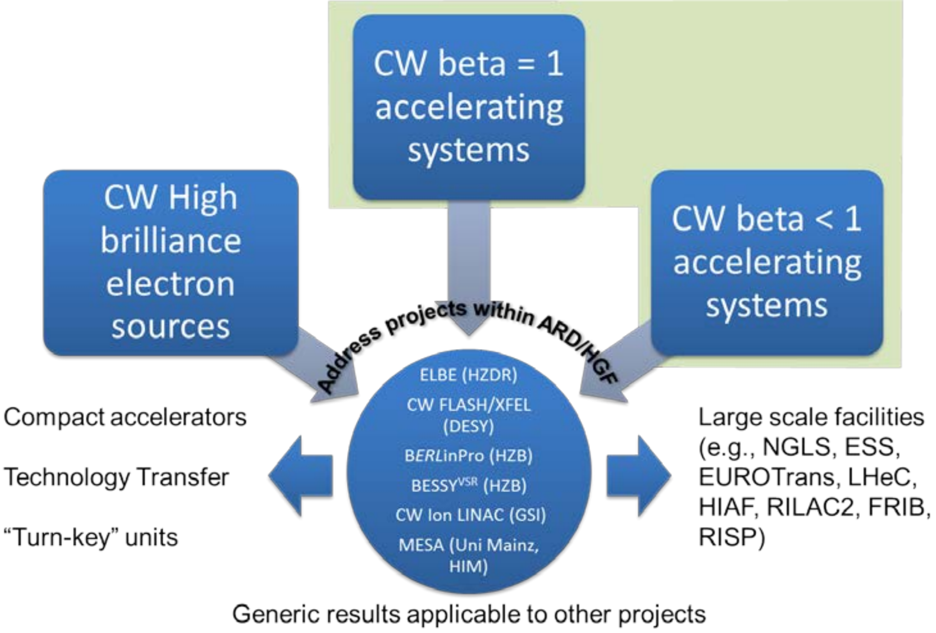


Figure 5: Connection between Subtopic 1 and "the rest of the world". (Note: A number of R&D areas for CW SRF are common to both low- and high-beta structures. This is indicated by the green box in the figure.)

3.1.1.2 Current Activities and Previous Work

While not all of the participating Centres (DESY, GSI, HZB, HZDR) are involved in all activities, each brings different expertise into the programme that, as can be seen from the publication list below, complement each other to cover the full breadth of ST1. In part, these activities build

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[1] *Pushing the ELBE RF system to high average beam current*, HZDR, Dresden, 14–15 March 2013 (http://indico.cern.ch/conferenceDisplay.py?confId=223797)

upon previous and existing collaborations such as the EuroFEL (funded by EU-FP6) collaboration on CW SRF (including, among others, HZB, HZDR, DESY), the informal GunCluster for CW SRF photoinjectors (HZDR, HZB, DESY, MBI), the International CW SRF Cryomodule collaboration, the much larger TESLA Technology Collaboration (TTC) or the European Collaboration on High Intensity Stable Beams (ECOS) within the European Nuclear Science and Applications Research (ENSAR).

DESY, HZB and HZDR are all members of the TTC, which laid the foundation for the technology planned for the International Linear Collider ILC. TTC was pivotal in developing SRF cavity designs and processing techniques for the required high-gradient pulsed operation. To test the SRF systems, the TESLA Test Facility (TTF) was constructed at DESY. It demonstrated the reliable, high-gradient operation of (pulsed) SRF cavities to accelerate high-brilliance beams and was so successful that TTF has now been converted to the FLASH free-electron laser. Its technology is the basis of the European XFEL at present under construction, thereby demonstrating how “generic” technology development can often lead to new accelerator applications.

Starting from the successful TESLA technology, an HZDR-led collaboration developed a CW-capable compact module operating at moderate gradient and current for use as a driver linac at the ELBE facility. This system also represents the baseline for a second-generation module capable of higher currents that is being developed by the International Cryomodule Collaboration. The module will soon go into operation at Daresbury Laboratory (UK). Based on the experience with ELBE modules, HZB has been actively pursuing a programme to further push TESLA systems for CW operation in GeV-class linacs, as for the formerly proposed BESSY Free-Electron Laser. Much of the R&D, such as active microphonic compensation schemes in CW-SRF units or CW-capable L-Band couplers, took place within the EuroFEL collaboration. To support this programme the CW-SRF dedicated infrastructure HoBiCaT was constructed. Even though the BESSY FEL was not funded, the expertise remains at HZB. Many aspects of its design are now being integrated into other projects, including B*ERL*inPro. It is an energy-recovery high-current CW linac being constructed by the Helmholtz Association that will ultimately be part of the ARD distributed test facility which is planned as a future research infrastructure within the Helmholtz roadmap. Currently new 1.3-GHz cavities capable of accelerating more than 100 mA in B*ERL*inPro are being designed. Given the user demand for CW FEL beams and given the successful first CW tests of TESLA systems, investigations of the changes required for CW operation of FLASH (and later perhaps XFEL) have started. This includes the on-going development of both high-power and low-level RF systems required for vector-sum operation of FLASH.

The centres participating in ARD have also been world-leading in terms of electron-source development. The PITZ collaboration that includes DESY and HZB, designed and operates a normal-conducting RF photoinjector test stand at DESY-Zeuthen, which has delivered the world’s most brilliant electron beam. Looking towards CW-capable systems an informal collaboration (GunCluster), comprising HZDR, HZB and DESY as well as the Max-Born-Institute (for lasers) coordinates the SRF injector development within the Helmholtz Associtation. Worldwide, the HZDR was first to demonstrate the feasibility of SRF photoinjectors and operates the prototype now routinely at a beamline (see), designed to accelerate moderate currents for ELBE. A second-generation system is currently being produced. Building upon this experience, the second stage of a three-stage programme to develop a 100-mA capable CW SRF injector will now be entered. In stage one, a Helmholtz-JLAB collaboration commissioned the world’s first-all superconducting (solenoid, cavity and cathode) SRF photoinjector at the HoBiCaT facility and the beam diagnostics line “GunLab.” This injector later will be the basis for a CW gun for FLASH.

Since the cathode is one of the critical components of photoinjectors, cathode production and analyses systems for various photocathodes are currently being set up. They are designed to study the surface science on a fundamental level for a better understanding of cathode performance in order to improve production and treatment techniques. Such measurements were performed in the past on PITZ cathodes using XPS at BESSY II and more recently have been expanded to the study of laser-cleaned Pb and CsK_2Sb cathodes with a number of analysis methods (such as GiSAXS, XRR, XRD, XPS). Importantly, a suitable common cathode and transport mechanism design has been developed to enable rapid exchange of cathodes between the labs' preparation and analysis chambers and injector cavities.

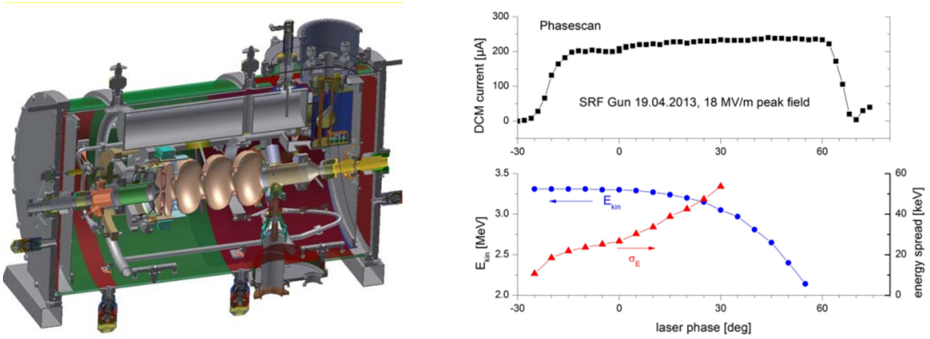

Figure 6: The world-wide first superconducting RF Photoinjector developed for routine, high-brilliance operation in a CW accelerator (ELBE). Right: Measurement of the extracted current, beam energy and energy spread versus RF phase.

RF losses will take on a central role in designing CW accelerators and consequently a programme is also being ramped up that studies the surface resistance of Nb and other superconductors. Fundamental studies have recently been performed to better understand the mechanisms of magnetic flux trapping in superconductors, a significant source of residual RF losses. These experiments included studies of the impact of metallurgy and cooldown conditions. Expanding on these experiments, neutron tomography was used to locate trapped flux in niobium samples. It was also shown that the thermo-electric effect during the cooldown of Nb samples can contribute significantly to flux trapping in niobium. In parallel, experiments with cavities suggest that indeed both the crystal structure and the cooldown conditions (thermal gradients) can have a dramatic impact on the RF losses (see, for example, Figure 7).

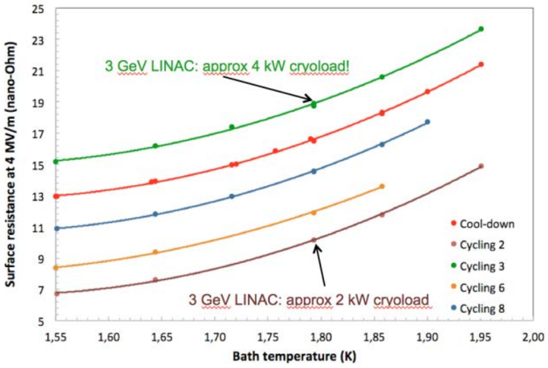

Figure 7: Surface resistance of a TESLA cavity for different cooldown conditions through the superconducting transition temperature. The difference between the worst and best case amounts to nearly 100% difference in cryogenic load at 1.8 K [12]. (Note: cycles 1, 4, 5, & 7 resulted in values near that given by cycle 2 and thus have been omitted from the plot for clarity.)

For rapid turn-around measurements a new dedicated sample test stand (quadrupole resonator) for high-resolution (surface resistance) RF studies is under construction. It will be used to study superconductor treatment techniques and new materials suitable for low-loss cavities to better understand their fundamental properties and performance before moving on to full SRF cavities to determine the technological applicability. This system can also be used to study recipes for cavity treatments (e.g., buffered chemical polishing, electro-polishing, barrel polishing) that have been developed by TTF to guarantee high-field cavity performance for pulsed linacs (see Figure 8). Presently the attention is turning towards developing similar recipes that are suitable for CW cavity operation, which can be tested first with samples and then with cavities on vertical test stands. These recipes will in future also find application in cavity treatments of low-beta as well as high-beta structures being developed by the Helmholtz-Institute Mainz (HIM).

Expanding CW SRF to the ion accelerator community, GSI has been developing, together with the Johann-Wolfgang-Goethe Universität Frankfurt, a CH structure that has the potential of becoming the enabling accelerating structure for a new CW heavy-ion linac (see Figure 9). Such a LINAC is designed to fulfil the ambitious requirements of the on-going super-heavy element programme as well as the demands of new material research and biology experiments. Currently a multi-cell CH-cavity is under development with the goal to operate a complete “demonstrator string” with beam at the GSI high-charge-state heavy-ion injector.

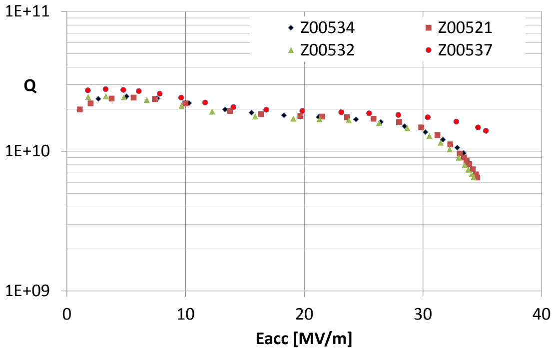

Figure 8: Cavity treatment techniques within the TESLA Technology Collaboration have consistently yielded high-field performance with little or no electron field emission

To support the existing SRF R&D programmes, a broad spectrum of infrastructure is now (or will be shortly) in place at the laboratories. It will prove pivotal for the planned collaborative and complementary effort. DESY has extensive infrastructure for the processing and assembly of cavities that has enabled HZDR and HZB to prepare cavities in the past. Several horizontal test stands at DESY were built to commission and qualify complete TESLA modules as used in FLASH and European XFEL and dedicated study time can be offered for selected R&D projects. HZDR operates the CW accelerator ELBE at moderate currents and runs a beamline for its SRF injector that has been used for measurements by the GunCluster. HZB operates the HoBiCaT test facility, dedicated for CW SRF tests of complete cavity units. HoBiCaT has already been used both by HZDR and DESY for CW component tests. It was recently expanded with a dedicated SRF injector research beamline for rapid access that was used by GunCluster to characterise two Pb-cathode SRF injectors. Later HZB will operate the B*ERL*inPro ERL facility that provides a test bed for studies of new accelerator concepts, SRF cavities and electron sources for high-current applications. Vertical test stands for extensive cavity tests are available at DESY and are being constructed at HZB, including one for basic R&D sample measurements. Such infrastructure is essential for supporting improved cavity design and for the RF characterization of new superconducting materials on a rapid turn-around basis. GSI, together with the Helmholtz-Institute Mainz (HIM) is in the process of building facilities for high-power tests of low-beta SRF modules as well as tests with heavy-ion beams from the GSI High Charge State Injector LINAC. HIM is also developing facilities to process and test both low-beta and beta=1 SRF cavities and to enable string assembly. Treatment techniques developed at DESY for beta=1 systems will serve as valuable input for this new facility

ARD will thus lead to significant advances in the field of CW SRF and continues to generate/upgrade infrastructure of a generic nature that provides for synergy effects between the laboratories. Importantly, often this infrastructure is the key for participation of universities in accelerator R&D, attracting many students, as well as for industrial partners to outsource activities for which the needed infrastructure otherwise would be prohibitively expensive.

University partners and international collaborators

For many R&D activities, university partners are included in the collaboration. Often, the universities are able to work on self-contained “sub-packages” while benefiting from the use of the laboratories’ extensive and expensive infrastructure. For example, TU-Dortmund is developing a transverse deflecting cavity for slice diagnostics of the beam from electron injectors which will then be installed at HZB’s “GunLab” SRF injector facility and later at B*ERL*inPro. Universities Rostock and Siegen are planning to develop cathode inserts that are multipacting free and which again will be tested at the ELBE and B*ERL*inPro facilities. Hamburg University is contributing with surface diagnostic techniques needed for SRF cavities. Further German universities that are currently involved in the joint research within ARD-ST1 (or will be in the near future) are: TU-Darmstadt, Goethe Universität Frankfurt, Universität Mainz and Universität Wuppertal.

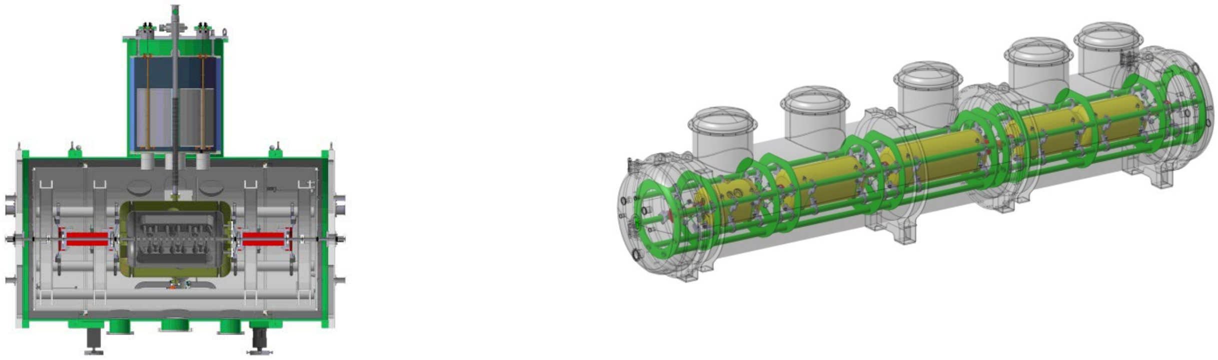

Figure 9: Single 15-cell CH-cavity cavity module for ion accelerators (left). Right: Draft version of a multi cavity advanced demonstrator layout [15].

On the international level, the collaboration partners include Cornell University, Michigan State University, Moscow State University, St. Petersburg State Polytechnical University, Stanford University, Brookhaven National Laboratory (USA), Daresbury Laboratory (UK), Jefferson Laboratory (USA), KEK (Japan), Lawrence Berkeley National Laboratory (USA), Max-Born-Institut (D), National Centre for Nuclear Research (Poland), Riken (Japan), IBS/RISP (Korea), and TRIUMF (Canada).

Industry partners

At present, industrial partners are primarily involved in component developments that have the potential for mass production for later large-scale facilities. For example, the concept for a 1.3 GHz semiconductor-based RF source for CW operation of ELBE accelerator modules was developed by Bruker in close cooperation with the HZDR. As a result a 10 kW solid-state amplifier system was put on the market. Such sources will be of great interest for compact CW accelerators or medium current CW LINACs such as FEL drivers. B*ERL*inPro will be using such units. Similarly, 500 MHz, 100-kW class units are being developed by Cryolectra for CW storage ring applications (here BESSY II) as an important alternative to klystron transmitters. Within the on-going ARD programme DESY is supporting the development of IOT sources at the company CPI as an option to operate FLASH or XFEL CW.

Along similar lines, recipes such as cavity treatment are being developed at the Helmholtz Centres (here DESY) and then transferred to industry (in this case Zanon and Research Industries) which allows for commercialisation of cavity production. The European XFEL is already benefiting from this technology transfer. But, importantly, this transfer also provides additional sources for cavity treatment, a common bottleneck, that in turn enables Centres without chemical facilities (e.g., HZDR, HZB) to pursue a vigorous SRF programme.

The drive for turnkey accelerating units is also being pursued in collaboration with industry. Early (non-Helmholtz) developments included the industrial production of 500 MHz CW-SRF units for storage rings by Research Intstruments (now installed at Cornell University, Diamond Light Source, Taiwan Light Source, Canadian Light Source). Similarly, and more recently, the compact 1.3 GHz CW SRF ELBE modules were transferred under the leadership of HZDR to industry (Research Instruments) and now are commercially available. They are used at ALICE/Daresbury and are on order for TARLA/University Ankara. In the latter case, cavity units will be prepared by RI, but acceptance tests are to take place at HZB’s HoBiCaT facility, illustrating nicely how the costly R&D infrastructure benefits accelerator development in general.

These and other industrial partners are also showing interest in other accelerator components developed in the HelmholtzCentres (e.g. HZDR SRF photo source, low-level RF systems for CW operation). Collaboration with industry was central to an ARD workshop held in March 2013 in Dresden.

Selected publications

[1] Overview on superconducting photoinjectors, Phys. Rev. Special Topics AB 14, 024801 (2011), A. Arnold, J. Teichert
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3.1.1.3 Objectives

ST1 is structured into two research fields that address the main challenges on the road to future new CW accelerators: “CW beam generation” and “CW beam acceleration.” Each of these areas, as shown in Figure 10, can loosely be subdivided into four research categories designed to focus the joint activities. However, these are not to be considered as rigid boundaries.

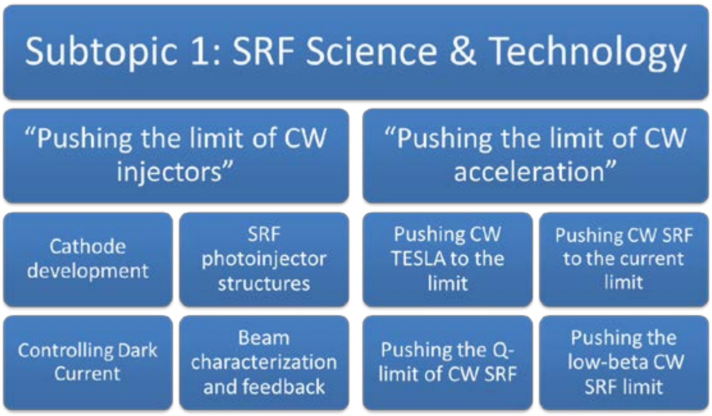

Figure 10: Structure of Subtopic 1: Superconducting RF Technology.

Pushing the limit of CW-electron injectors

Many new electron accelerator applications not only require CW operation but also demand electron sources that must be able to deliver CW beams with an exceptionally high brightness. The objective here lies in controlling beam emission in short pulses, accelerating rapidly to reduce non-linear space-charge effects, handling high beam loading and providing a system that can operate reliably for long periods. Laser-operated photo-injectors, whereby a laser pulse illuminates a cathode to eject electrons by the photoelectric effect, represent the state-of-the-art in this respect. Different approaches (DC injector, normal-conducting RF injectors) have proven very successful but have inherent drawbacks (e.g., DC injectors are limited to about 500 keV acceleration, NC-RF injectors are limited to pulsed operation due to cooling constraints). Far less explored but with possibly the greatest potential are superconducting RF photo-injectors because they can fulfil the goal and operate CW both at high gradient and voltage simultaneously. The Helmholtz Association is world leading in this development, with the first routinely operating SRF injector being commissioned by HZDR. While the feasibility has been demonstrated, many open issues must be resolved before such units can be employed in next-generation accelerators. These include the development of high-quantum efficiency cathodes with long lifetimes (many days rather than minutes/hours), their integration into a superconducting environment, operation at higher fields (> 15 MV/m) to achieve low emittance at high bunch charge and the control of dark current which, if left uncontrolled, severely limits the operation of future high-energy CW linacs.

Cathodes for CW SRF LINAC injectors

Common to all photo-injectors, irrespective of their subsequent acceleration concept, is the photo-cathode whose electron emission is triggered by a short laser pulse synchronised with the subsequent accelerating field. Ideally the cathode has a high quantum efficiency (QE = number of electrons emitted per incoming photon), a reasonably low work function so that long-wavelength lasers can be employed, a prompt response (< 1ps) to generate short pulses and to enable pulse shaping, and a long cathode lifetime before the degradation of cathode necessitates its replacement. A common system in use is CsTe which however does not fulfil all of these requirements (e.g., its work function requires UV laser light and its QE is low). An alternative is GaAs, which also is suitable for the generation of polarised electrons that are of interest for nuclear physics such as at MESA. But its response is not prompt and its QE suffers if the vacuum exceeds the 10^{-10} mbar range. Both systems are normal conducting thus requiring complex configurations to integrate them into an SRF cavity.

ST1 will therefore concentrate on studying and improving photocathodes and learning how to integrate these into an SRF environment. For a range of accelerator applications different cathodes may be considered and a broad spectrum needs to be investigated. Expanding on the previous work, methods for surface and semiconductor characterization will be applied and developed for an understanding of the formation of photocathode layers and the mechanism of electron emission from these. Crystal lattice structure, chemical compound formation and the influence of impurities will be studied. This knowledge will point the way to improving the quantum efficiency and other relevant parameters. Another research topic will be the relationship between surface morphology and the thermal emittance. New materials, multilayers and nanoscale surface structure will also be investigated with the aim to tailor photocathodes for specific applications.

Each partner will concentrate on different cathodes and aspects that ultimately complement each other. For moderate currents and pulse lengths (as in HZDR's ELBE) GaAs is an attractive choice since it simplifies the laser system (IR). High-charge but low-average-current (< 1 mA) operation at a CW optimized FLASH/XFEL requires highest gradients so that DESY will pursue a novel programme that is based on a superconducting Pb cathode. For highest currents and short pulses CsK_2Sb cathodes promise a long life time and prompt response and will be pursued by HZB for the B*ERL*inPro project. While the material is different in each of the cases, the production/analysis techniques and hardware have commonalities that are already being exploited to push a highly collaborative programme. The objective is to develop the techniques to produce such photocathodes, ideally in standardised configurations, and to have them subjected to long term characterisation and reliability tests at the Helmholtz testing facilities.

Looking to the longer-term future new ideas will need to be explored. For example, HZDR eventually wants to implement “pulse combs” that allow the emission of several bunches in a single RF cycle for few-cycle and multi-cycle THz radiation production at ELBE. Here as well new photocathodes with very short response times (< 1 ps) yet still high quantum efficiencies must be developed. New materials or structured cathodes may hold the key to such applications.

Expertise in cathode production and characterisation from university and external partners (e.g., Universität Mainz for GaAs and CsTe and National Centre for Nuclear Research, Poland, for Pb, Brookhaven National Laboratory for CsK_2Sb) is being integrated into the Helmholtz programme. A joint German-Russian collaboration between HZB, HZDR, Universität Mainz, Moscow State University and St. Petersburg State Polytechnical University (SPbSPU) is designed to study high-brightness beams from photocathodes in general.

Photoinjector hardware: High-gradient and high-current SRF photo-injectors

The beam generated at the cathode must be accelerated rapidly to prevent emittance dilution and pulse lengthening due to space-charge fields. For practical reasons (diagnostics, focusing elements, pumps), the following accelerating structures will be located a fair distance from the injector so that ideally the injector will provide a large accelerating field *and* a large voltage. The voltage in DC accelerators is limited to about 500 kV. Copper RF cavities can provide much higher voltages and fields but are limited to pulsed operation due to excessive power dissipation. Only SRF units can provide both high field and high voltage while operating CW. ST1 thus aims to develop SRF units that

- are optimised from a beam dynamics point of view
- are optimised to operate at high field with extremely little unwanted beam
- incorporate an NC cathode without adversely affecting the cavity’s RF performance
- handle large beam loading (if required by the accelerator application)
- are able to provide excellent field stability to enable the required synchronisation between the generated beam and the RF field.

Similar to the cathode development, the partners will concentrate on different aspects as dictated by the accelerator application, which complements each other to provide answers to all of the abovementioned issues. Both HZDR and HZB are collaborating on developing a “standardised” design for the incorporation of the NC cathode into the SRF environment while avoiding the presently encountered limiting problems (e.g., multipacting in choke filter units). Beyond this, HZDR will concentrate on a cavity unit that is able to provide the highest voltages at moderate currents as dictated by the ELBE application. Such a structure will consist of several accelerating cells. HZB, on the other hand, requires high-current acceleration for BERLinPro and high-current light sources, and the voltage will be limited by the RF input couplers. Hence a few-cell design (< 3) is being designed and the focus shifts to a high-power coupler system that minimally disrupts the beam. DESY will pursue the development of an all-superconducting system with an SC-Pb cathode. While such a system will never provide >1 mA current, its lack of the disruptive NC-cathode makes such a system attractive for high-bunch charge operation (nC) where highest fields are required, such as for free-electron laser applications.

These activities also rely on university partners. For example, HZDR and HZB are planning a collaboration with Universität Rostock and Universität Siegen to develop multipacting free inserts by developing new structure designs and surface treatments.

Once robust SRF injectors are developed the focus will turn towards novel operating modes that extend the flexibility of accelerators being driven by these sources. E.g., HZDR plans to include “multibeam” operation, whereby phase shifted laser pulses extract beams from the linac at multiple energies simultaneously.

Controlling the unwanted beam from high-current CW electron sources

Field emission, laser halo, scattered laser light etc. will result in spurious electrons being emitted in the injector cavity. Thus, many design aspects from laser beam transport to laser in-coupling to the cavity structure design and the cathode material will impact the amount of this so-called unwanted beam. A significant portion will be transported through subsequent linac sections and can result in uncontrolled beam loss at high energy. In CW machines these losses will put significant stress on accelerator components or cause additional cryogenic losses. Worse still, the generated bremsstrahlung and neutrons can place a severe burden on the radiation shielding. Storage ring facilities have beam-loss rates which vary between a few pC/s (BESSY II) to a few hundred pC/s (PETRA III in high bunch charge mode, where radiation damage in undulators starts becoming an issue). Translated to a 1.3 GHz CW LINAC for new applications, such as ERLs, this value implies an equivalent loss rate of a staggeringly low 3×10^{-9} - 10^{-7} pC, or less than one electron per bunch.

For many high-energy CW applications, the unwanted beam has the potential to severely impact their feasibility. A major objective of ST1 will therefore be the diagnosis of unwanted beam, understanding the source/cause (e.g., cavity, cathode, stray laser light) of the unwanted beam and learning how to control any unwanted beam that is transported out of the SRF photoinjector (e.g., dark current kickers, collimators). Ultimately, all three aspects will play a vital role in readying SRF photoinjectors for modern linac applications.

Many aspects can be studied in detail with the injector test stands that are being developed to characterise photoinjectors, as well as at ELBE and later B*ERL*inPro. In addition, dedicated systems will be developed to study the intrinsic field-emission characteristics of photocathodes as these are, due to their low work function, especially likely to field emit. This R&D activity should ultimately help identify cathode materials, and production techniques that provide cathodes with very low dark current.

International interest in this work package was underscored by the attendance of an ARD workshop on unwanted beam recently organized by HZDR and HZB[2]. University partners participate in these research activities within the framework of the *Verbundforschung* to better understand the emission from photocathodes and the generation of dark current. As part of the Helmholtz-Russian Joint Research Group (HZB-BINP, Novosibirsk), dark current studies and halo control is also being studied.

Beam characterisation and operational issues

CW accelerators of the next generation need to deal with special beam diagnostic challenges that result from the high-average power, extreme beam parameters and high bunch repetition rates (up to GHz). While beam diagnostics per se is not an SRF specific issue, ST1 will include a focus on those aspects that are required to support the photo-injector and SRF linac development. In particular these include the emittance measurement, bunch-length measurement and the dark current/beam halo characterisation. Such diagnostics will be integrated into the test beam lines at ELBE and B*ERL*inPro, all of which will be well suited for long-term studies of SRF injectors. Another goal will be to use information from diagnostics for fast feedback on the LINAC/ source operation for beam stabilisation. The challenge of beam characterisation will also be addressed in synergy with the activities in ARD-ST3 (eg. regarding the development of THz-based diagnostics). These diagnostics will be sufficiently generic so that they can be integrated into different test facilities and future accelerators.

Since the goal of the SRF injectors in most cases is to provide a highly brilliant beam for many modern accelerator applications these facilities will also be used to develop techniques to yield the lowest possible emittance. Three approaches are currently being envisaged and will be studied for beam focusing as close as possible to the SRF injector: (a) Magnetic field of a superconducting solenoid (b) photocathode shaping, or the recent idea to (c) use the magnetic field of a TE cavity mode.

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[2] "*Unwanted beam workshop 2012"*, 17–18 Dec. 2012, HZB, Berlin, https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2

Again, university partners are associated with these activities and the potential exists to expand the collaborations. For example, slice diagnostics via transverse deflecting cavities are in operation at FLASH/ DESY and are being developed by HZB in association with TU-Dortmund for beam characterization. The latter will be optimised for ERL operation, running CW for low-energy beams and will be able to make measurements both horizontally and vertically with the same system.

Pushing the limits of CW SRF acceleration

The second work area deals with the challenges of providing CW acceleration for highly brilliant beams that often consist of short pulses and carry a high current. Present technology (e.g., TESLA) has some headroom to be adapted for CW operation and one ST1 objective is to take the technology to its limit. But issues such as RF power transmission/beam loading and broadband HOM extraction/damping place limits on how far these systems can be pushed. The objective of ST1 thus will be to develop “next-generation” SRF units capable of operating beyond TESLA’s capabilities, especially regarding beam current and cryogenic load, both of which will dominate the feasibility of next-generation CW accelerators.

Pushing TESLA technology for CW operation

TESLA technology has gone through more than two decades of intense development for a linear collider (ILC) and free electron lasers (FLASH/XFEL). It was specifically designed to operate at highest gradients, thereby necessitating pulsed operation at about 1% duty cycle to limit the cryogenic load. However, since 2000 it has been shown that it also has the potential for CW operation. Light-source concepts such as NGLS (USA), BESSY FEL (Germany), 4GLS (UK) all plan(ned) to use TESLA-like technology. In fact both the ELBE and ALICE accelerators have demonstrated that its operation at moderate gradients and beam currents (< 15 MV/m, < 1 mA) is indeed feasible. A recent ARD workshop[1] explored how to increase the average current. And since TESLA technology has achieved near-turnkey status it may be considered for many accelerator types including compact machines operated by laboratories that are not specialised on accelerators. Beyond this, the European XFEL and FLASH facilities are trying to address the x-ray-user demand for CW operation by developing CW upgrade scenarios.

Previous R&D has demonstrated the CW potential of TESLA technology, but numerous limitations were identified that are to be addressed by ST1. These include

- Issues associated with high-average RF power operation (e.g., input and HOM couplers) that exceeds the present limit of TESLA accelerating structures.
- Issues associated with precise control of the RF field in the narrow-bandwidth cavities. Modern applications require control down to the 0.01 deg level.
- Development of reliable and cost effective RF sources for CW operation.
- Development of CW-capable higher harmonic units required to linearise the longitudinal phase space in modern LINACs.

The participating Centres will each contribute to these objectives in different areas that, put together, complete “the puzzle.” DESY will concentrate on developing the technology for CW operation of XFEL while HZDR is focused on upgrading ELBE, thereby pointing the way towards future compact accelerators. HZB is adapting the technology to be used in future ERL applications and brings its expertise in CW development related to the former BESSY-FEL project into the collaboration. Collaborations outside Helmholtz are also being pursued, including with leading international SRF labs such as Jefferson Laboratory with whom both HZDR and HZB have Collaborative Research and Development Agreements (CRADA) in place for cavity production and treatments.

Pushing the current limit of CW SRF

TESLA technology was designed to accelerate up to a few 10s of µA average current, and 10 mA beam current within the pulse train. For CW operation the limit is probably in the 1 mA range. Higher currents are limited on the one hand by the RF system and on the other hand by the HOM generation, extraction and damping. Many new accelerator applications for light sources (LINAC and storage-ring based), electron coolers, and compact sources require significantly higher average currents, up to several 100 mA. For example, ERL units will need to accelerate 100 mA (+ 100 mA for the deceleration pass). Multi-cell L-Band SRF cavities have yet to demonstrate such performance, and new cavity designs to minimise the generation of HOMs while enabling their simple extraction and extinction near room temperature must be developed.

ST1 aims to develop generic new systems for such high-current applications. Initial designs will concentrate on waveguide-damped units that can be employed in B*ERL*inPro, to explore their capabilities. Their design builds on ideas originally developed at Jefferson Laboratory who will be involved as a collaborating partner. However, the generic character of the work package lends itself to expanding the scope to systems that can be employed, for example, as overvoltage cavities in storage rings for operation up to several hundred mA. One example is BESSY^{VSR} designed to produce ps short pulses in the BESSY II 1.7-GeV synchrotron light source. The concept is being developed in sub topic ST3 but the design of the necessary SRF systems will be an objective of ST1. This idea has generated international interest and is being considered for other light sources (e.g., SPEAR3). The scope of the units developed here can also be expanded to CW FEL light sources (e.g., NGLS) or for higher-harmonic units (see the above section) as linearisers.

At present, the main development work is being pursued by HZB in collaboration with universities (Rostock Universität, TU-Dortmund) and international partners (including Jefferson Laboratory and Cornell University) while HZDR provides additional know-how (e.g., via the International CW Cryomodule Collaboration that also includes Cornell University, Daresbury Laboratory, BNL, LBNL, Stanford University and TRIUMF) and DESY is contributing via by providing cavity treatment and testing infrastructure.

Pushing the Q limit of CW SRF to manage cryogenic losses

While the goal for pulsed SRF units for large-scale XFEL or even ILC-like applications has been to push the achievable gradient to the maximum possible to minimise the number of cavities in the driver LINAC, this aspect moves somewhat into the background for CW operated facilities. For GeV-class machines the cryogenic load dictates that present cavities operate at or below 20 MV/m. Even so, cryogenic plants need to deliver a nearly prohibitive capacity of order 10 kW at 2 K. Similarly, smaller, 10-100 MeV-class “compact” accelerators are hard to realize in a cost effective (and low-maintenance) manner because the cryogenic plant dominates the cost and adds significant complexity. This has been a large hurdle for the industrialisation of SRF facilities.

For this reason, the achievement of high quality factors will be an important objective of the CW R&D. The gap between the currently achieved values with Nb cavities (ca. $1-2\times10^{10}$) and that theoretically possible (ca. $2-3\times10^{11}$) is huge. Even the field dependent BCS resistance is not yet fully understood. Measurements have also shown that the attained Q-factors depend on the cavity treatment techniques and operating conditions (e.g., cavity cool-down procedure) with a resultant Q spread up to a factor of two. An understanding of these effects is still lacking and subject of intense R&D to better understand the surface resistance of niobium. The goal is to define treatment techniques that will enable reliable high-Q operation above 15 MV/m.

Beyond this, many new and exciting avenues, such as the treatment of niobium with nitrogen to achieve Q-factors in excess of 9×10^{11} at 1.8 K and 1.3 GHz were reported on at the most recent SRF Conference and will be the subject of further investigation. If a better understanding of such systems can developed and the performance is reproducible then they will dramatically impact the operation of future large-scale CW accelerators

Moving beyond niobium, several new superconductor systems (including Nb_3Sn and multilayer systems) hold the promise of achieving even higher Q-factors or the same value as niobium but at higher temperature. Recent experiments with Nb_3Sn demonstrated Q-factors in excess of 10^{10} at 4.2 K (@1.3 GHz). If their promise can be realised then superfluid-helium-operation no longer is necessary and the cryogenic plant can be significantly simpler and less expensive.

Perhaps even cryogenic coolers can be employed one day, thereby making a dramatic contribution to “turnkey” operation of small CW accelerators.

For a systematic investigation of these superconducting systems a two-prong approach is chosen. Sample measurements with the quadrupole reasonator will enable controlled measurements over a wide range of temperatures, fields and frequencies to fully characterize both the BCS and residual resistance. These experiments should yield a better understanding of the underlying physics. In parallel, cavity measurements with suitable diagnostics (e.g., thermometry) permits the study of the technological applicability of the best treatments identified.

While this research field has the potential to make a significant contribution, the participating Centres presently do not possess the infrastructure to produce superconducting films and to characterise these. Hence the initial effort will concentrate on developing sample testing infrastructure to quantify the RF performance of materials, including niobium, and identifying external collaborators for the production of thin film superconductors.

Pushing limit of CW SRF for ion accelerators

Fundamentally, many of the objectives stated above apply to both high and low-beta cavities and a fair fraction of the R&D finds equal application for both ion and electron accelerators. However there are some design and treatment issues that are unique to low-beta cavities.

Primarily the R&D will concentrate on the development of Crossbar H structures for heavy ion accelerators, which are being pursued by GSI together with HIM. Furthermore, the Goethe Universität Frankfurt and Universität Mainz provide a large collaborative effort in developing the CH SRF structures.

Multi-cell CH cavities allow for a compact and highly efficient LINAC design. For this reason the SRF CH-cavity has developed into a prominent option for a number of accelerator projects. The R&D challenges include pushing the accelerating gradient to a higher level by appropriate designs and treatments, the development of sufficiently powerful CW RF couplers and the efficient cavity cleaning and handling procedures needed to handle the relatively complex and long structures. Given that superconducting 10 T solenoids are in the immediate vicinity of the cavities in accelerator modules, shielding and compensation schemes must also be developed and the impact of the remaining field on the cavity operation must be investigated. This activity is of significant international interest (e.g., FRIB @ MSU, ISAC @ TRIUMF, RISP @ IBC, HIAF @ IMP) and is being investigated in collaboration. It also was the subject of a recent workshop held at MSU.[3]

Recent R&D efforts already succeeded to push the performance of low-beta ion LINACs to a new frontier. They range from tests of a 360-MHz, beta = 0.1 SRF CH-cavity prototype with 19 gaps up to 7 MV/m to the design of a beta = 0.06, 15-gap cavity for the new ion CW-LINAC demonstrator operating at 217 MHz. The objective of ST1 is to continue this development to ultimately deliver a fully CW-operating system installed at the GSI “CW accelerator” and ready for use in other ion accelerators.

Interestingly, there also have been ideas (outside the Helmholtz Association) to adapt low-beta structures (e.g., spoke cavities) to electron accelerators, illustrating that the low- and high-beta worlds are not necessarily separate.[4,5] The benefit lies in the fact that for a given size the spoke cavities run at fairly low frequencies, thus permitting operation at higher temperature and thereby simplifying the cryogenic plant. Building on results from this and the other ST1 objectives, in combination with suitable electron sources, such units may eventually be a very interesting option for turnkey compact accelerators.

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[3] 2013 Workshop on Magnetic Shielding for Cryomodules, FRIB, MSU., 6-7 March 2013.

[4] J. Delayen, “Application of spoke cavities”, *Proc. LINAC 2010*

[5] M. Sawamura et al., “Design optimization of spoke cavity of energy-recovery LINAC for non-destructive assay research”, *Proc. SRF 2011*.

3.1.1.4 Timelines of Activities and expected Results

Years	Cathode development	Participants
on-going – 2015	Develop recipes and handling techniques for photocathodes for SRF injectors (presently GaAs, CsK_2Sb, Pb)	HZDR, HZB, DESY
2015 – 2016	Characterise the performance of cathodes in test beamlines and ELBE	HZB, HZDR, DESY
2015 – 2019	Long-term studies of cathode performance and lifetime issues at high current at ELBE and (later) B*ERL*inPro	HZDR, HZB
2016+	Development of cathode materials for new ideas (e.g., pulse-comb generation)	HZDR

Years	Injector hardware development	Participants
2015	Completion of new designs for cavity units for medium-current, high-current and high-charge CW applications	HZDR, HZB, DESY
2015 – 2017	Characterisation of injector systems in test beam lines, ELBE, and B*ERL*inPro	HZDR, HZB, DESY
2017 – 2019	Study of high current (>10 mA) and high charge (> 100 pC) beams from SRF photoinjectors	HZB, DESY
2017+	Development of phase and energy-shifted multi beams from an SRF injector	HZDR

Years	Avoiding unwanted beam	Participants
2015 – 2016	Study of intrinsic field emission from photocathodes	HZB
2015 – 2017	Characterisation of dark current at ELBE and HZB injector test stand, later also at DESY injector	HZDR, HZB, DESY
2015 – 2017	Development of mitigation schemes for dark current (e.g. dark current kicker and collimation)	HZDR, HZB
2017 – 2019+	Beam halo/unwanted beam characterisation during high-current CW operation (> 10 mA) @ B*ERL*inPro	HZB

Years	Beam characterization	Participants
on-going – 2017	Develop and implementation of new diagnostics for detailed injector characterisation at ELBE and “Gunlab” injector facility and possibly later at 2nd XFEL injector line	HZDR, HZB DESY
2015 – 2017	Study of efficacy of various emittance compensation schemes and demonstration of lowest CW beam emittance	HZDR, HZB
2016 – 2019+	Development and tests of fast diagnostics-based CW beam stabilisation schemes (combines with activities in ST3)	HZDR, HZB, DESY
	CW TESLA	Participants
on-going – 2016	Development and test of efficient high-power RF systems for CW TESLA operation at ELBE and CMTB	HZDR, DESY

on-going – 2015	Development and demonstration of new concepts (e.g., vector-sum LLRF and active microphonics compensation) for field control in CW TESLA-type units	DESY, HZB
2017 – 2019	Construction and test of a CW-capable 3.9 GHz linearizer cavity system	DESY

Years	**High average current**	**Participants**
2015 – 2016	Development of CW overvoltage cavities suitable for pulse compression in storage rings (concept development in ST-3) based on results from B*ERL*inPro and new ideas	HZB
2016	Prototype tests using DESY and new HZB infrastructure	HZB, DESY
2017 – 2018	Characterization of B*ERL*inPro and BESSY$^{\text{VSR}}$ high-current accelerating systems & first beam tests	HZB
2018 – 2019+	High current operation of CW SRF L-Band systems in B*ERL*inPro and implementation in BESSY$^{\text{VSR}}$ (see ST-3)	HZB

Years	**Dynamic RF losses**	**Participants**
on-going – 2016	Develop & define Nb-cavity treatment and operating techniques for reliable high-Q operation above 15 MV/m	DESY, HZB
2016 – 2017	Study of surface resistance of Nb samples, expand studies to other superconducting systems. Results feed back on treatment techniques for high-Q operation	HZB
2017 – 2019	Collaborative (with int. partners) effort to produce coated cavities based on results achieved with samples	HZB, DESY

Years	**Low-beta specific issues**	**Participants**
on-going – 2015	Development of injector infrastructure @ HLI for module testing with beam	GSI, HIM
2015 – 2016	Characterize CW-LINAC CH-cavity demonstrator with beam	GSI, HIM
2016 – 2019	Development of multicavity CH system based on previous beam tests for GSI CW accelerator	GSI, HIM
2016 – 2018	Develop CH cavity treatment techniques for high field operation that expands on high-beta cavity recipes (see above). Integrate new techniques in the cavity preparation and testing infrastructure being constructed at HIM.	HIM
2019+	Beam tests of CH module at HLI and subsequent implementation at GSI CW accelerator	GSI, HIM

3.1.2 Concepts and Technologies for Hadron Accelerators

The ARD subtopic 2 focuses on the development of advanced and new technologies for hadron accelerators. Here, FZJ and GSI (including HI-Mainz and HI-Jena) cooperate to reach common objectives, together with German universities and international collaboration partners. Cutting-edge research for hadron accelerators requires a complex and highly developed infrastructure as it is available at the involved Helmholtz centres. In the second round of programme oriented funding (PoF-II), the development of new accelerators und large scale facilities for science belongs to the core activities of the Helmholtz programme “Physics of Hadrons and Nucleus”. The main goal of the two involved Helmholtz centres is the development and construction of the new international accelerator complex FAIR (Facility for Antiproton and Ion Research). According to a decision of the Helmholtz Senate these activities of GSI and FZJ that are directly related to the construction of FAIR, are exempted from the PoF-III evaluation. To provide a full picture of the ARD activities we report in the following – for information only- on the R&D work happening at GSI and FZJ on hadron accelerators.

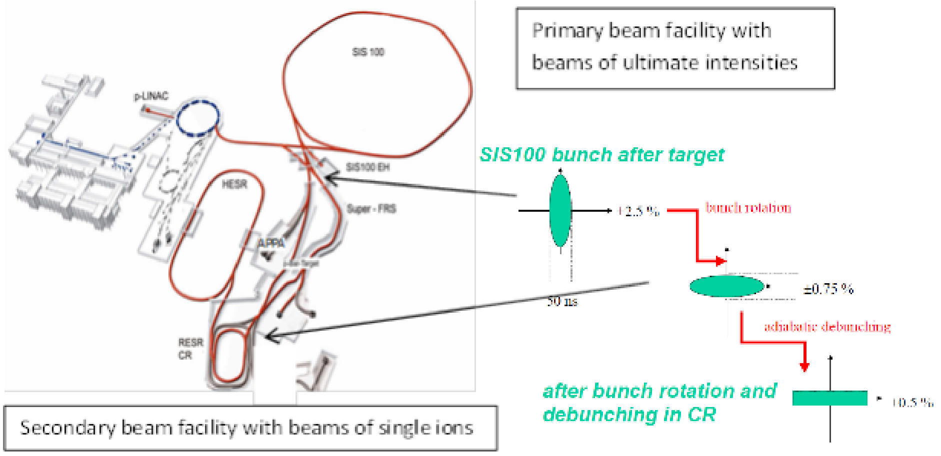

Figure 11: Hadron accelerator facilities consist of a primary beam facility which provides beams of highest intensities well matched to a production target and to the subsequent secondary beam facility. Due the low cross sections, the primary beam facilities have to approach the stability limits of intense beams, while the secondary beam facilities often deal with beams of single ions. Shown is the typical bunch matching and processing in the FAIR accelerator chain SIS100 - production target - storage ring CR.

3.1.2.1 Challenges

An important feature of hadron accelerators is the generation of secondary beams at high kinetic energies such as radioactive ion beams or antiproton beams. For this purpose, large accelerator complexes are being built which typically consist of a primary beam facility, dedicated production targets and separators, followed by a secondary beam facility. Due to the low cross sections for the production of secondary beams, the primary beam intensities must be pushed to the limits, while the beams of the secondary ions consists often of only a few particles. Furthermore, the ion bunches generated by the primary beam facility must be well matched longitudinally and transversely to the production targets and the subsequent secondary beam facility (Figure 11). Therefore, facilities of hadron accelerators have to cope with beams of extreme parameters, demand a wide spread of different accelerator technologies and an enormous dynamical range of the involved machine components. In the following the different activities which cover R&D with outstanding importance for such accelerator complexes are described. In addition, R&D work towards the realization of a high-precision experiment on the electric dipole moment (EDM) of the proton and deuteron is part of the activities in this subtopic.

Ion sources for future Hadron Accelerators

At FAIR-GSI, a great variety of intense beams of ions from protons up to U are requested, including beams of rare isotopes. Such beams of heavy ions must be provided to the accelerator facility in routine operation with highest reliability, reproducibility, and stability. To achieve a significant increase of ion beam intensities from an ECR ion source (ECRIS), an enhanced plasma density is required. According to semi-empirical scaling laws and experiments the electron density is directly related to the square of the microwave frequency. Suitable electron densities can be achieved with the use of 28 GHz microwave heating. For proper radial plasma confinement, the increased microwave frequency requires a stronger magnetic hexapole field with values above 2 T at the wall of the plasma chamber. In addition, a mirror field for axial confinement is required with two maxima in the range of 2 - 4 T. These values can only be achieved by using superconducting magnets for the solenoid coils generating the mirror field as well as for the hexapole. A SC-ECRIS is characterized by a high versatility, a low material consumption leading to a high efficiency, good beam stability and low beam noise. The adjustable axial and radial magnetic fields enable optimum adaptation to different working points. The production of the highly charged ions facilitates the injection into a LINAC without post-acceleration.

Another issue for future hadron accelerators is the development of ion sources for polarized beams. For the new antiproton synchrotrons HESR/FAIR and ELENA/CERN, beams of positive or negative polarized ions have to be delivered for optimizing the performance of the complex accelerator and dedicated detector systems before availability of antiprotons. Many of the next-generation accelerator applications are only feasible if high performance, polarized ion sources will be available.

Superconducting magnet technology

For future hadron synchrotrons, fast cycled magnets of superferric (iron-dominated with superconducting coil) and cosθ designs have to be developed. Due to the fast cycling, AC-losses are induced which have to be minimized to enable safe operation. As key components, new superconductors with fine filaments and a higher resistive interfilamentary matrix have to be developed. Similar developments are needed also for new future projects, e.g. SIS300 or upgrades of existing machines as for example CERN´s PS and SPS rings. Therefore, GSI is aiming for a continuation of the developments in these fields. Even technical combinations as for instance using a Nuclotron type hollow cable for building a cosθ magnet are considered. For future, so called stretcher synchrotrons (constant operation at low field levels), superconducting wires with even smaller filaments are needed to obtain sufficient field quality. Also for the improvement of the superconducting cable itself, future R&D work is required.

Septum magnets for beam injection and extraction are characterized by a comparably thin septum blade between extracted/injected and the circulating beam and are typically operated at the limit of cooling power. This blade consists of two vacuum chambers, a coil with its insulation, a stainless steel sheet and a magnetic screen all comprised in a space of only some 10 mm. Higher magnetic field strengths as they are required for example for high rigidity beams, can only be realised with superconducting coils. In this case, the magnet as a whole has to be cooled down in a cryostat. Due to the sensibility of the superconductor’s stability to small movements, the mechanical structure of such magnets is an issue. The need for higher magnetic strength in future machines will increase the need for such superconducting septa, which are at the edge of the technical feasible.

For the next generation of final focusing systems for intense heavy ion beams, superconducting quadrupole magnets with apertures considerably larger then presently available are required. High intensity heavy ion beams are typically generated with large emittances. Thus, quadrupole apertures in the order of several hundred millimetres are needed. On the other hand such large apertures lead to high magnetic forces. Since any deformation of the coil leads to enhanced field errors, the mechanical stability of the magnets becomes a big issue. The development of such large aperture magnets is therefore a challenging task for future accelerator applications.

Ultimate heavy ion intensities

The aim of the planned FAIR accelerator complex at GSI is to provide heavy ion beams with intensities far beyond what is currently available for experiments. To provide ultimate high intensities of heavy ion beams, medium charge states are required, e.g. U^{28+}. However, in collisions with residual gas molecules, such intermediate charge state heavy ions suffer from high ionization cross sections and can change their charge state. Caused by the charge difference to the reference ion, and consequently difference in magnetic rigidity, such ions are lost with high probability at aperture limiting insertions. At the point of impact, gas molecules are released via ion stimulated gas desorption. Thereby, a local pressure rise is generated and the probability for further charge exchange processes is increased. The generated vacuum instabilities are a limiting factor for the maximum reachable intensities of heavy ion beams.

Longitudinal Feedback Signal Processing

Beside acceleration of particles in synchrotrons and storage rings, Rf cavity systems enable several options for manipulations and methods for stabilization of ion beams. Stabilization of the beam can be achieved by means of longitudinal feedback systems. Thereby longitudinal oscillations within a heavy ion synchrotron can be attenuated, e.g. dipole- and/or quadrupole oscillations within a bunch, as well as coherent oscillations between bunches, can be stabilized.

High sensitivity, high time resolution, non-destructive in ring particle detectors

Stored stable and/or radioactive highly-charged ions (HCI) offer unprecedented opportunities for high-precision interdisciplinary investigations essential for a variety of applications, e.g. for accelerator physics, nuclear structure and reactions, atomic physics, astrophysics, testing of fundamental symmetries and interactions. The experimental results on HCI are strongly demanded and often cannot be provided by any other technique or method. However, the experiments are highly complicated. The important prerequisite for these measurements is the ability to produce stable or radioactive ions of interest in high atomic charge states, purify them from unwanted contaminants and then store and cool them for extended periods of time. The latter is only possible in the ultra-high vacuum environment of a storage ring. Presently, the main interest lies in the production, separation and storage of beams or rarely produced exotic ions, which are of inevitably low-intensity down to single particle beams. Preparation of such beams puts highest demands on accelerator diagnostics tools.

Injector Linac

New high-energy heavy ion injector linacs optimized for operation at high beam intensities may replace existing RF structures traditionally used as injectors for synchrotrons. Exploring the limits of surface electric fields and acceleration gradients as well as to assure highest operation reliability are major research topics. Besides the potential application for the FAIR injector linac, the development of such accelerating structures is of general interest for all modern ion linacs.

Target Development for Stored Slow Beams

The use of solid and gaseous targets is well established in accelerators for stripping of ions to achieve a more efficient acceleration. They are also used widely in atomic and nuclear physics for collision experiments. However, in connection with the stringent limits concerning space and vacuum in storage rings when it comes to low beam energy and high charge states as foreseen at FAIR, they represent a major challenge.

Development and tests of a laser cooling pilot facility for heavy ion beams

Future accelerator facilities will provide high-energy beams of stable and rare (heavy) ions for fundamental research. Planned experiments, such as in-ring mass spectrometry of short-lived rare nuclei, tests of strong-field QED with highly-charged ions, or x-ray and laser spectroscopy of atomic transitions, will greatly benefit from ion beams with an ultra-low momentum spread. However, the high cost and the demanding technical efforts to realize electron cooling at such high energy E_b are the main reasons why other methods were considered for the FAIR HESR and the SIS100.

Laser cooling is a very promising alternative because the laser cooling force increases with the third cube of the beam energy, and cooling times can be as short as milliseconds. At the future high-energy facilities, many different ion species can be addressed by state-of-the-art laser systems due to the relativistic Doppler-shift of their cooling transitions. Furthermore, at high E_b -values, the fluorescence from the laser-excited ions is emitted in a strongly forward-peaked cone, which supports accurate laser spectroscopy of atomic transitions (SPARC @ FAIR).

Development of high-field E/B deflectors and high-precision spin dynamics for dedicated EDM storage rings

Different approaches to measure Electric Dipole Moments (EDMs) of proton, deuteron and light nuclei are pursued at Brookhaven National Laboratory (BNL) and FZJ with an ultimate goal to reach a sensitivity of 10^{-29} e·cm in a dedicated storage ring. As an intermediate step, a first direct EDM measurement of protons and deuterons at 10^{-24} e·cm sensitivity level will be carried out in a conventional storage ring, the Cooler Synchrotron COSY at FZJ. To perform this kind of precision experiments high-field static and RF E/B deflectors have to be developed. Major development steps are the optimization of the shape of electrostatic field plates with suitable magnet field configurations and R&D work on surface treatments that can yield high electric field gradients.

Full particle and spin-tracking simulations of the entire experiment are absolutely crucial to explore the feasibility of the planned storage ring EDM experiments and to investigate systematic limitations. For a detailed study of particle and spin dynamics during the storage and buildup of the EDM signal, one needs to track a large sample of particles for 10^9 turns. Existing spin tracking codes like COSY-Infinity (M. Berz, MSU) have to be extended to properly simulate spin motion in presence of an electric dipole moment. The appropriate EDM kick and electromagnetic field elements (static and RF) have to be implemented and benchmarked with other simulation codes.

The physics and experimental developments of the Electric Dipole Moment (EDM) measurements at Jülich are covered by the programme "Matter and the Universe" in topic "Cosmic Matter in the Laboratory ".

3.1.2.2 Current activities and previous work

Ion sources for future Hadron Accelerators

A versatile concept of a fully superconducting ECRIS working with radial magnetic fields of up to 2.1 T and with microwave frequencies of 28 GHz has been adopted by the RIKEN Nishina Centre for Accelerator-Based Science, Japan. Its flexible arrangement of the superconducting coils allows for a variable adjustment of the longitudinal magnetic field profile.

The availability of polarized and unpolarized ion beams with the maximum possible intensity has to be assured for COSY operation at FZJ and for commissioning of future antiproton facilities at CERN and FAIR. Promising experience with versatile nuclear polarized atomic beam sources, charge exchange reactions as well as the long-standing successful operation has been obtained at accelerators at IUCF, Bloomington and at the cooler synchrotron COSY, FZJ. Especially the collaboration with INR will help to make a plasma ionizer for polarized ion sources available in Jülich.

Superconducting magnet technology

New superconductors with fine filaments and a higher resistive interfilamentary matrix were developed for the FAIR synchrotrons SIS100 and SIS300. Up to now only very few superconducting septa have been investigated. GSI has conducted a preliminary design study in collaboration with BINP. Superconducting quadrupole magnets are under development for apertures up to 150 mm but not for larger apertures. Design work for the 2nd generation fast ramped cosθ magnet has been started within the European CRISP project and co-financed also with funds from the ARD implementation phase. For 2013, the manufacturing of a collared coil is planned.

Ultimate heavy ion intensities

In the past years the vacuum instabilities, which are also called “dynamic vacuum” have been investigated at GSI and several counter measures have been developed. The progressive implementation of these counter measures enabled a significant increase of the maximum intensity of accelerated heavy ion beams in SIS18 to more than $3{\cdot}10^{10}$ particles per pulse. The interaction between beam and residual gas can be described by the STRAHLSIM code, which has been developed at GSI, and is worldwide unique. STRAHLSIM allows the prediction of the efficiency of upgrade measures for further increased intensities.

Longitudinal Feedback Signal Processing

A broad band MA cavity, dedicated for longitudinal feedback, is presently under development funded within the ARD implementation phase.

High sensitivity, high time resolution, non-destructive in ring particle detectors

A first prototype cavity detector has been developed during the on-going ARD programme. This cavity has demonstrated excellent performance in the ESR [1, 2] and a similar detector is being commissioned in the CSRe storage ring at the IMP, Lanzhou, China. Moreover, a first prototype cryogenic current comparator (CCC; SQUID based magnetic flux detector) has been developed allowing for non-intercepting and absolute current measurements with a high sensitivity even for low-intensity beams.

Injector Linac

Conceptual design studies have been performed of a 108 MHz IH-type linac for acceleration of high-current uranium ion beams from 1.4 MeV/u to 11.4 MeV/u and of a 325 MHz energy booster linac based on CH structures. This includes the preliminary design of a prototype IH cavity and preliminary studies for a 1.8 MW, 108 MHz rf amplifier and digital LLRF systems for the construction of a high-power rf test bench. Furthermore, charge stripping tests of high current uranium ion beams at the GSI UNILAC with methane and hydrogen gas strippers and carbon foils and related thermal stripper foil simulations were done to investigate options to optimize the stripping efficiency and to increase the ion charge states.

Target Development for Stored Slow Beams

Two partner universities develop transversal electron targets and are about to define the most suitable technologies for slow beams. Additionally, the development of a target with polarized electrons has been started in a collaboration of the universities in Giessen, Frankfurt and Jena and the Helmholtz Institute Jena. A prototype magneto optical trap used as a target in a storage ring exists in Heidelberg. It has been successfully tested in the TSR, a low energy storage ring, very similar to CRYRING@ESR. First results using atom ensembles cooled and stored in magneto optical traps have been obtained for light species.

Development and tests of a laser cooling pilot facility for heavy ion beams

Laser cooling experiments have been performed at the ESR at GSI. Technical solutions have been implemented for: Novel cw and pulsed laser systems, (X)UV-beamline, laser beam transport and stabilization over very long distances, (*in vacuo*) fluorescence detection systems for diagnostics and spectroscopy, control and data acquisition systems.

Experiments have been performed with fast sweeping of the laser frequency and beam cooling has been successfully demonstrated during a beam time at the ESR (GSI) in 2012.

Development of high-field E/B deflectors and high-precision spin dynamics for dedicated EDM storage rings

Development and tests of an RF B deflector with polarized beams in COSY and development of a low-field RF E/B deflector are on-going. The transfer of an electrostatic deflector from FNAL to

Jülich is being prepared. The implementation of electromagnetic (E/B) field elements (static and RF) and EDM spin kick in simulation programme for beam and spin dynamics is taking place.

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3.1.2.3 Objectives

Ion sources for future Hadron Accelerators

GSI will perform the production of a SC magnet system required for the ion source, including the cryogenic systems and ancillary equipment. After the SC magnet system is available at GSI, it will be commissioned at the dedicated ECRIS test facility. Subsequently the SC magnet system will be assembled with the ancillary equipment to achieve the completion of the SC-ECRIS. As such an ion source is a complex system of various components a careful and sophisticated commissioning has to be performed. Therefore, intensive R&D will be performed at the test facility to achieve the optimum operating conditions for operation at the accelerator. An improved ion extraction system adapted to the enhanced extracted ion currents shall result in efficient beam formation and transport. Finally the device will be transferred to the injector of the accelerator followed by the commissioning at the accelerator together with the dedicated low energy beam transport system.

A polarized ion source, based on the proven concept of resonant charge exchange of a pulsed, nuclear spin-polarized atomic beam with an intense plasma beam, appears as the appropriate approach for future applications. The achievements at the nuclear spin-polarized atomic beam part will be useful to improve COSY operation. In further steps, a plasma ionizer to produce an intense hydrogen ion beam will be designed and implemented. Particular focus is the study of the brilliance of the extracted ion beams, in addition to the reliable and reproducible generation of high intensity beams. Initially, the existing polarized ion source at FZJ, the INR test source and JINP’s polarized source for NICA serve as models. Simulation and experimental verification through analysis and study of the parameter dependencies of the sources are intended. After availability of a plasma ionizer in Jülich, it will be analyzed and extended with a pulsed nuclear-spin-polarized atomic beam to a polarized ion source. Currently a pulsed ion source and a short beam line, foreseen for delivery of positive and negative ions at ELENA/CERN, have been assembled and are now operational. This source is prepared for delivery of intense, short – micro second – pulses with reversal of the extraction scheme for positive and negative charged ions. Control system and diagnostic tools have to be developed according to the required performance.

According to the results of ongoing research and analysis of existing sources and their subsystems, a new polarized ion source can be designed and built in the period 2015-2019. The developments will be carried out together with the cooperation partners CERN, BNL, INR, RIKEN Nishina Centre for Accelerator-Based Science, RWTH Aachen and U-Bonn. The demonstration of the availability and identification of weaknesses in long-term operating environment will be performed at the accelerator facility COSY and its infrastructure.

In summary, the objectives of these activities are to provide high performance sources for hadron accelerators at COSY, CERN, FAIR and for other future accelerators for light, polarized and heavy ions of any required charge state, including the development and validation of advanced components and diagnostic tools for ion sources.

Superconducting magnet technology

In the next years, completion of a full magnet shall be reached (implementation of iron yoke and He-container). After the assembly, the magnet has to be cooled down and electrically and magnetically tested. For a full characterization of the magnet an upgrade of the existing prototype test facility at GSI has to be carried out. In the frame of the proposed developments, an improved, curved cosθ dipole magnet, based on the DISCORAP project by GSI and INFN is planned.

Starting from already existing design ideas developed together with BINP (a patent by GSI is pending) the design of an SC septum magnet has to be finalized. A short prototype magnet and a full size septum magnet have to be built and tested at cold.

The work to be carried out for the large aperture superconducting quadrupole magnets comprises the design of the magnet, manufacturing of the first prototype and the full size magnet and finally the testing of these magnets.

The international partners participating in this activity are INFN Genova, Milano and Salerno, ASG Genova, IHEP-Protvino and BINP-Novosibirsk.

Ultimate heavy ion intensities

The data basis for the STRAHLSIM code is still incomplete. Especially the pumping speed of cryogenic surfaces and the ion-impact induced gas desorption of cryogenic surfaces plays a major role in the development of the vacuum dynamics. Measurements of desorption yields at the prototype cryocatcher for the SIS100 showed a contrary energy scaling as it is known from room temperature measurements. Aiming for an optimized design of heavy ion accelerators for high intensity heavy ion operation, cryogenic ion-impact induced gas desorption needs further investigation.

For the systematic investigation of the pumping surfaces of cryogenic surfaces a dedicated test stand will be constructed. Sticking coefficient and mean sojourn time as a function of surface coverage and temperature of the surface shall be measured. The obtained results will be implemented in the STRAHLSIM code to predict the long-term stability of the vacuum system in superconducting synchrotrons. Also at room temperature predictions about the saturation behaviour of NEG surfaces are required. The results will improve the STRAHLSIM simulations for warm synchrotrons.

The desorption scaling of the room temperature ion catcher system of SIS18 needs a dedicated investigation. Fast pressure diagnostics shall be installed in SIS18 in order to measure the partial and total pressure evolution during a cycle. Since the maximum reachable collimation efficiency in an existing synchrotron, like SIS18, is limited by the existing ion optical layout, new approaches have to found to catch lost ions in a controlled way. By this reason new collimation concepts shall be investigated, e.g. a vacuum chamber with a saw-tooth-like surface. Such a geometry provides a perpendicular surface for incident ions, which minimizes the desorption yields.

Injection and extraction septa are typically positioned close to the circulating beam. Such they are always potentially a matter of beam loss. To keep the pressure rise as low as possible, new geometries for electrostatic septa shall be developed and investigated. Such a septum will have a low desorption yield and a high pumping speed.

Due to the improved understanding of the dynamic vacuum, it will be possible to further reduce the dynamic pressure bumps in SIS18 during the upcoming long shutdowns. While SIS18 is not available, further investigations of ion impact gas desorption will be performed at a test stand which will be setup at the AGS-beam at BNL.

As cooperation partners U-Frankfurt and TU-Darmstadt are participating in the activities described here.

Longitudinal Feedback Signal Processing

The objective of this activity is the technical verification of a bunch by bunch longitudinal feedback system. This subprojects aims for realization and characterization of the components such a feedback system and for the set-up of a complete prototype system. Within the BMBF-project (FKZ 05P12RDRBF) one scientist at TU-Darmstadt supports the study by elaborating the system topology. The capital investment from the PoF-III funding will be used for material expenses as well as another scientist who will be in charge of assembling, commissioning and characterization of the overall system.

The main focus of the project will be the signal processing system for the feedback system. A basic requirement for the feedback system and therefore for the signal processing system is the measurement and the manipulation of a bunch without any influence of other bunches.

Beside the basic requirement the following requirements have to be fulfilled:

- Wide dynamic range of the feedback system
- De-multiplexing of the time intervals for the individual bunches
- Fast and flexible signal processing
- Signal generation for the kicker- cavity for the attenuation of the oscillations within the bunches
- Multiplexing of the signals for all bunches on one cavity

The broadband and the narrowband measurement by means of a dedicated beam diagnostics system is the first goal of the longitudinal feedback system, followed by the development of the signal processing system. This signal processing system determines and generates the appropriate signal for the manipulation of the beam. Thus, the signal will be transmitted through an amplifier to a broadband cavity used as a kicker cavity. It is planned to reuse and adapt the broadband cavity currently developed within the PoF-II ARD- project. The effort for the adaption of the cavity will be determined during the project time.

Cooperation partners are the “Institutes for Automation Technology and Mechatronics” (IAT) und for the “Institute for Theory of Electromagnetic Fields” (TEMF) of the TU-Darmstadt.

High sensitivity, high time resolution, non-destructive in ring particle detectors

For the multipurpose diagnostic applications at radioactive ion beam facilities like at GSI, in-ring detectors must have a broad dynamic range being able of measuring milliamps of stored beam down to single stored ions—the ultimate sensitivity; they have to be very fast that also the short-lived radioisotopes can be detected, and last but not least they have to be broad-band to be able to monitor stored multi-component ion beams. Furthermore, a possibility to apply such detectors for the measurements of transverse beam temperature, beam position or ultimately the amplitudes of betatron oscillations must be investigated.

The development of appropriate detectors is needed for the present ESR at GSI and is essential for the CRYRING facility, which is being re-assembled right now behind the ESR. Furthermore, the experience and the developed detectors themselves will also be indispensable for the design of the corresponding detectors for the FAIR storage rings. Additionally, slow extraction from the SIS100 synchrotron requires diagnostic devices for non-destructive measurement of ion currents down to the nA- region. For this purpose, the installation of Cryogenic Current Comparators (CCC) is foreseen, offering a non-intercepting and absolute current measurement. In order to achieve the ultimate sensitivity of the CCC, improvement of the SQUID-detector and optimization of the flux sensor is subject of ongoing.

The university partners participating in this activity are FSU Jena and U-Frankfurt.

Injector Linac

A linac for short beam pulses (≤ 100 μs), low repetition rate, and fixed end energy is already under investigation at GSI. Highly efficient room-temperature IH-type cavities with high acceleration gradients are state-of-the-art for ion acceleration in terms of RF efficiency in the low beta range (up to $\beta \approx 0.12$). Optimized field design as well as development and tests of prototype IH and CH cavities are required to expand the energy range of H-mode structures for ion acceleration up to $\beta \approx 0.2$, in particular, for high-current heavy ion beams. The proposed R&D is aiming for the development and tests of 108 MHz / 325 MHz IH and CH cavities for acceleration of high-current heavy ion beams up to $\beta \approx 0.2$. The university partner U-Frankfurt (Inst. for Applied Physics IAP) is participating in this activity.

Target Development for Stored Slow Beams

In order to advance the possibilities for collision studies the scientific community requests two target types that are on the verge of applicability for stored particle beams but not quite there yet. Longitudinal electron targets have delivered outstanding results starting with beam cooling to experimental insights like di-electronic recombination cross sections and their dependence on the nucleus. However, a transverse electron target would open up new collision regimes with the challenge to prepare them dense enough for the assumed reaction cross sections and the possibility to prepare them with polarized electrons. In gaseous targets the available densities are dominated by the achievable pumping speed and this limited. There are liquid targets on its way to be introduced into storage ring devices, but to get to really high densities a possible way would be to go to atom ensembles cooled and stored in magneto optical traps. However, especially for the heavy ions available at GSI and FAIR an equally heavy collision partner would be desirable. This could for instance be mercury, which is well established in the MOT field, but is not available yet as target material in storage rings for low energy beams.

The work here will focus on the development of electron targets for storage ring environments, i.e. ultra high vacuum and only limited accessibility. Special features are also the requirements on remote control as well as temperature resistance during bake out. Those limit the available technologies and will need extensive research and development planned to be performed here.

To advance the target developed for the TSR to heavier particles, an appropriate laser system has to be developed and integrated into the storage ring environment. The major work here is to achieve the required stability even though there might be much longer distances between laser installation and storage ring. This requires sophisticated temperature stabilization systems and powerful fiber connections to be integrated within this project.

The university partners in this activity are U-Frankfurt, U-Gießen and MPI for Nucl. Phys. Heidelberg.

Development and tests of a laser cooling pilot facility for heavy ion beams

Laser cooling of relativistic ions in storage rings or synchrotrons can be performed using only an anti-collinear laser beam and a bunched ion beam. However, the bandwidth of a cw laser is typically of the order of a MHz and therefore too small to collect the initially `hot' ions (momentum spread $\approx 10^{-4}$). In order to compensate for this mismatch, two approaches, using different laser systems, will be investigated. 1) The frequency of a cw laser is rapidly tuned over a broad range, thereby cooling ions with corresponding velocity classes. 2) The combination of a fixed cw laser, tuned close to the resonance at the desired velocity class, and a pulsed laser with a large bandwidth, can address a broad range of ion velocity classes simultaneously. The second scenario, which is very promising, needs to be tested at present (GSI, IMP) and future facilities (FAIR).

Upcoming efforts must then be focused on laser development (HZDR, TUDa), laser beam transport and stabilization (HZDR, GSI, TUDa), and proper diagnostics, such as fluorescence detection (GSI, TUDa, WWU), Schottky resonators (GSI, HI JENA), beam profile monitors (GSI), and control and data acquisition (GSI, IMP). In order to prepare for a laser cooling pilot facility at FAIR, additional tests and beam time are required. These could be performed at the ESR or the upcoming CRYRING facility (GSI). At CRYRING, tests of laser beam transport and stabilization, as well as tests of the control and data acquisition systems could be performed. In parallel, a very active collaboration (HZDR, GSI, TUDa, HI JENA, WWU, IMP) has started the preparations for laser cooling at the CSRe (IMP), which will complement the preparations at GSI and FAIR.

The university and international partners in this activity are TU-Darmstadt, U-Münster, IMP-Lanzhou.

Development of high-field E/B deflectors and high-precision spin dynamics for dedicated EDM storage rings

The stepwise approach of the EDM Project is starting with the R&D work at COSY, the first direct measurement of a charged particle EDM at COSY, and the design of a dedicated storage ring. The studies of spin coherence time and systematic studies will be performed with a low-power RF-E/B spin flipper with an electric field gradient of tenth of MV/m. For the first direct EDM measurement with a sensitivity goal of at 10^{-24} e·cm a high-power RF-E/B spin flipper is required with an electric field gradient of more than 1 MV/m with a B-field of roughly 70 G in a frequency range of 0.1 to 1 MHz. The construction of a dedicated EDM storage ring to reach ultimate sensitivity goal of 10^{-29} e·cm, BNL is pursuing the proposed proton EDM with a purely electrostatic bending field whereas the feasibility of an “All-In-One” lattice design with combined electrostatic and magnetic field deflectors is investigated in Jülich to perform a deuteron or helium-3 EDM experiment, which is complimentary to the proton EDM measurement. For an EDM storage ring of radius r = 30 m transverse electric fields of 17 MV/m with a magnetic field up to 1.6 kG are required.

To study subtle effects and simulate particle and spin dynamics during the storage and buildup of the EDM signal, one needs custom-tailored fast trackers capable of following up to 100 billion turns for samples of up to 10^6 particles with high-precision for spin rotations of roughly 10^{-18} radians per element. Furthermore, a symplectic description of fringe fields, field errors, and misalignments of magnets has to be adapted and verified. In order to provide the required CPU time for the simulations of spin motion with a time scale larger than tens of seconds, spin tracking programmes have been migrated to powerful computer systems. A project for the Jülich supercomputer (JUROPA) started in November 2012. Finally, benchmarking experiments will be performed at the Cooler Synchrotron COSY to check and to further improve the simulation tools. In a next step, the analysis of systematic spin rotations will be carried out. Spin tracking for a first measurement of a charged particle EDM in a storage ring can be performed to investigate the sensitivity of the proposed method. Finally, the layout of a dedicated storage ring has to be optimized by a full simulation of particle and spin motion.

The utilized simulation programme COSY-Infinity is based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle. It includes higher-order nonlinearities, normal form analysis, and symplectic tracking. The upgrade of COSY-Infinity will be supervised by M. Berz, the principal developer of the presently available version of this powerful tracking tool.

Given the complexity of the tasks, particle and spin dynamics simulations performed with COSY-Infinity must be benchmarked with other simulation programmes and experiments performed at the Cooler Synchrotron COSY.

The integrating method, even though it is slow, is used for benchmarking the results of the much more efficient COSY-Infinity. In addition, numerical integration of the Thomas - BMT differential equations for a spin motion with smoothly approximated parameters of orbital motion can be used to benchmark all simulation programmes.

The university and international partners participating in this activity are RWTH Aachen, BNL, FNAL, MSU and StPSU. The RWTH Aachen University is our participating strategic partner and strongly contributes to the development of high-field E/B deflectors. In a close collaboration with us, the Physics Institute and the High-Voltage Institute of RWTH is going to develop and test static high-field deflectors to reach non state-of-the-art performance. The High-Frequency Institute is supporting our efforts to develop RF deflectors with innovative technologies. The Physics Institute is also strongly involved in the development of high-precision spin dynamics. Several theses by students from RWTH are in preparation. The strong partnership between RWTH Aachen University and Forschungszentrum Jülich is established by JARA - Jülich-Aachen Research Alliance. In this well-proven scientific environment the research field JARA-FAME (Forces and Matter Experiments) focuses on basic physical research in the field of nuclear and particle physics, and aims to investigate and improve our understanding of matter-antimatter asymmetry in the universe.

3.1.2.4 Timeline of activities and expected results

Years	**Ion source development**	**Participants**
2015	Commissioning and optimization of the SC magnet system	GSI
2015+	Operation of the ELENA source at CERN	FZJ, CERN
2016 – 2019	Commissioning and operation of the 28 GHz SC-ECRIS	GSI
2015 – 2019	Design and detail studies for polarized sources (p, d, He$_3$) for future facilities	FZJ, INR, Universities
Year	**Superconducting magnet technology**	**Participants**
2015	Completion of septum and quadrupole magnet designs	GSI, INFN, ASG, IHEP
2015 – 2016	Production and tests of magnet prototypes	GSI, INFN, IHEP
2016 – 2017	Production of full size magnets	GSI, IHEP
2018 – 2019	Successful cold tests of septum and quadrupole magnets	GSI, IHEP

Years	**Ultimate heavy ion intensities**	**Participants**
2014	Experiments on cold desorption at SIS18, measuring the pumping speed of cryogenic surfaces	U-Frankfurt, TU-Darmstadt
2015	Commissioning of the experimental area at AGS (BNL), integration of measured physical parameters (sticking coefficient, sojourn time) into the StrahlSim code to calculate cryogenic pumping speed	U-Frankfurt, TU-Darmstadt

2016	Modifications of SIS18 to increase the UHV pumping speed, further measures to suppress vacuum dynamics, installation of additional UHV diagnostics, investigations and tests of an electrostatic wire septum	U-Frankfurt, TU-Darmstadt
2017	Completion of the SIS18 upgrade programme, re-commissioning of SIS18 with medium charge state heavy ions, acceleration of $5 \cdot 10^{10}$ uranium ions per pulse	U-Frankfurt, TU-Darmstadt
2019	Reaching the space charge limit for medium charge state heavy ions.	U-Frankfurt, TU-Darmstadt

Years	**Longitudinal Feedback Signal Processing**	**Participants**
2015	Conceptual design of the signal processing	TU-Darmstadt
2016	Realization of a prototype of the bunch- by – bunch de-multiplexing	TU-Darmstadt
2018	Overall system consisting of signal processing and broadband cavity assembled	TU-Darmstadt
2019	Conclusion of investigation regarding signal processing in combination with a modified broadband cavity	TU-Darmstadt

Years	**High sensitivity, high time resolution, non-destructive in ring particle detectors**	**Participants**
2015	Simulations of the detector, conceptual design, and preparing the initial infrastructure	GSI, FSU Jena, U-Frankfurt, HI JENA
2016	Design of the detector and the data acquisition system	GSI, FSU Jena, U-Frankfurt, HI JENA
2018	Manufacturing of the detector prototype and supporting-subsystems	GSI, FSU Jena, U-Frankfurt, HI JENA
2019	Installing of the detector in the storage ring and the full commissioning of the entire system: detector-data acquisition-data analysis/monitoring system	GSI, FSU Jena, U-Frankfurt, HI JENA

Years	**Injector Linac**	**Participants**
2015	Beam dynamics studies and determination of optimum energy for frequency jump 108 → 325MHz	GSI, U-Frankfurt, HIM
2016	High-power 108MHz RF tests on test bench	GSI, U-Frankfurt, HIM
2016 – 2017	High-current ion beam tests with prototype cavity	GSI, U-Frankfurt, HIM
2019	Tests of high-power cavity	GSI, U-Frankfurt, HIM

Years	Target development for slow stored beams	Participants
2013 – 2016	Adaptation and integration of a transverse electron target for UHV and characterization of major parameters	U-Frankfurt, U-Giessen, GSI
2016	Demonstration of new transverse electron target in the storage ring environment	
2014 – 2017	Transformation of an in-Ring MOT into a Hg-MOT target for CRYRING@ESR	MPI-K Heidelberg, HI JENA, GSI
2017	First experiments with Hg-MOT target in CRYRING@ESR	MPI-K Heidelberg, HI JENA, GSI

Years	Development and tests of a laser cooling pilot facility for heavy ion beams	Participants
2014 – 2015	Development of a broadband pulsed laser system and characterization and tests at HZDR and TUDa (a fast scanning cw laser system will also be present)	GSI, HZDR, HI JENA, TU-Darmstadt
2016 – 2017	Tests of the laser systems and diagnostics: @ IMP Lanzhou: CSRe. @ GSI: ESR and CRYRING. Tests of control and data acquisition systems.	GSI, HZDR, HI JENA, TU-Darmstadt, WWU, IMP
2017 – 2018	Installation of the laser systems: SIS100 (set up beam lines and diagnostics)	GSI, HZDR, HI JENA, TUDarmstadt, WWU, IMP
2018 – 2019	Pilot experiments for FAIR with heavy ion beams: HESR and SIS100	GSI, HZDR, HI JENA, TU-Darmstadt, WWU, IMP

Years	High-field E/B deflector & simulation programmedevelopment for EDM storage rings	Participants
2013 – 2016	Development and construction of a low-field RF E/B deflector and spin dynamics experiments at COSY	FZJ, RWTH
2013 – 2018	Transfer of an electrostatic deflector from Fermi Lab to Jülich, refurbishing and performance test, installation in COSY and beam test	BNL, FNAL, FZJ, RWTH
2014 – 2015	Benchmarking of E/B field elements with spin experiments at COSY and EDM spin kick with other simulation programmes	FZJ, MSU, StPSU, RWTH
2015 – 2017	Detailed simulations of first direct EDM measurement at COSY	FZJ, RWTH
2015 – 2019	Development and construction of a high-field RF E/B deflector, conditioning and installation in COSY and first direct EDM measurement in COSY	FZJ, RWTH

2015 – 2019	Design study of a static E/B deflector, construction, conditioning and test bench	FZJ, RWTH
2018 – 2019	Systematic error investigation of a dedicated EDM storage ring	FZJ, RWTH

3.1.3 Picosecond and Femtosecond Electron and Photon Beams

During the past decade, accelerator technology has advanced towards the generation of ultra-short electron bunches which enable the production of picosecond and femtosecond photon pulses for the investigation of processes in atoms, molecules, solid states, and biological systems.

Without accelerators, research on these processes has been carried out using mode-locked lasers which are powerful in the optical and near infrared wavelength range, but wavelengths outside of this range were inaccessible with high powers and high peak electric fields. Short-pulse accelerators fill this gap, allowing for the production of long wavelengths in the THz regime and short wavelengths in the hard X-rays, often simultaneously. The outstanding tuneability and power of accelerator-based short pulse facilities offer opportunities for cutting-edge science and have attracted worldwide scientific interest from researchers in many fields. This interest imposes increasing demands on the availability, stability, brightness, flux, and duration of the accelerator generated light pulses.

The substantial investment costs of accelerator based light sources make them a rare commodity for photon users, industrial or medical applications. R&D in the field of ps-fs beam sources therefore includes to make the accelerators more compact with reduced beam energy and to optimize the performance and potential of large facilities facility which serves multiple users simultaneously by improving the photon beam repetition rate, quality, flux and stability.

3.1.3.1 Challenges

Short-pulse beams require precise and fast controls with high demands on diagnostics and instrumentation, a deep understanding of the complex beam dynamics, and careful numerical simulations benchmarked by experimental results. These short-pulse accelerators can serve as injectors to plasma wakefield accelerators, deliver user-tailored THz pulses with high peak and average power, generate half-cycle mid-infrared light pulses or produce fully coherent XUV and X-ray light with (sub-) femtosecond pulse duration. The existing infrastructure within the Helmholtz shall be optimally used by defining common test facilities and joint projects for the generation and characterization of ps–fs electron beams.

This research has major impacts on the photon user community and pioneering advances for linear and circular accelerators can be expected.

The research activities within ST3 are structured into three major areas (see **Figure 12**):

- **Beam Dynamics & Photon sources:** ultra-short bunch and photon pulse generation and shaping in linear and circular accelerators for wide parameter ranges in bunch length, charge and beam energy
- **ps-fs Beam Diagnostics:** development of high resolution beam diagnostics for temporal-spatial distributions covering large dynamical range with high data throughput
- **Stability, Controls & Synchronization:** standardized real-time feedback (MicroTCA) with high data volume processing and pushing the technological limits of tolerances on the accelerator RF controls and laser stability.

These fields are common to all ps-fs short pulse production efforts. To make optimal usage of pre-existing know-how and research strengths of the Helmholtz centres and associated cooperation partners, close collaboration is systematically fostered through technology transfer and networking activities between accelerator facilities and university groups. An integral part of this effort are the ps-fs test facilities planned within ST3.

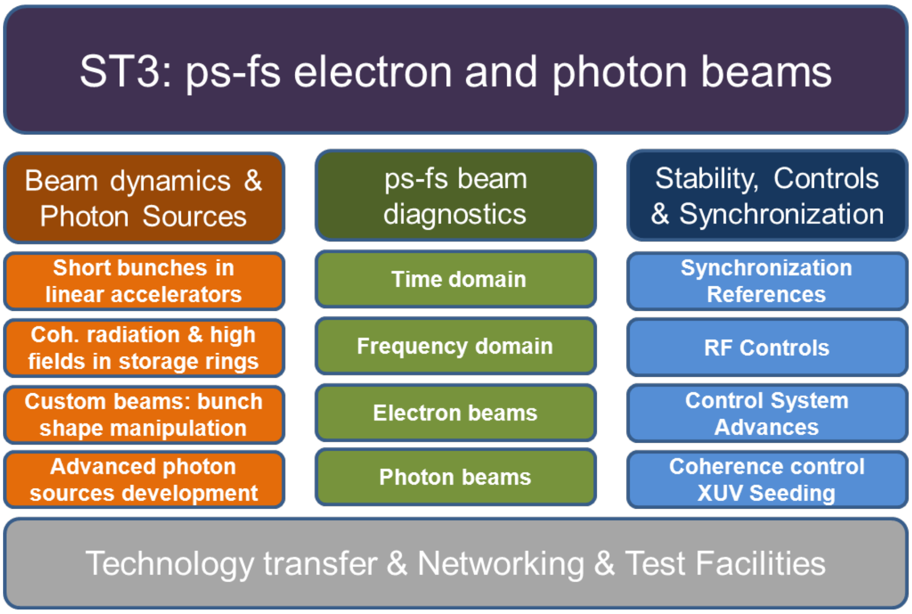

Figure 12: Structure of subtopic 3.

Within the current PoF II period it became apparent that the field of ps–fs beam diagnostics for low energy electron beams could make better use of the infrastructure available within the Helmholtz by defining specific test facilities which offer unique research opportunities. Currently, three test facilities for ps-fs low-energy electron beam diagnostics have been identified:

- FLUTE: test facility for single-shot diagnostics
- PITZ: test facility for electron beams in the burst mode
- TELBE (THz at ELBE): test facility for quasi-cw electron beams.

FLUTE, which will come into operation in 2014, offers the opportunity to generate electron bunches with charges ranging from few pC to 3 nC at a repetition rate of 10 Hz. This enables the study of novel single-shot monitoring systems over an extremely wide dynamic range. Since another aim of FLUTE is to achieve bunch lengths down to 1 fs (for 1 pC), it can additionally serve as a test bed for beam diagnostics and dynamics for future plasma wakefield injectors, thus providing a close link to ST4. FLUTE as a test accelerator also allows for easy access to tests of diagnostic components which require reconfiguration of the accelerator layout. Upgrade options for FLUTE using major investment funding at KIT are considered in the PICCOLO („Pretty Intense COherent and Compact Light sOurce“) project plan. PITZ provides the exact same burst mode pattern of FLASH and of the European XFEL. It furthermore possesses a unique photo-injector laser which allows for the generation of particular longitudinal bunch shapes while offering access to a transverse deflecting cavity longitudinal bunch shape monitor. TELBE offers unique access to Europe’s only quasi – CW electron beams with repetition rates up to 13 MHz and bunch charges from the pC to 1nC. All aforementioned electron linacs offer opportunities to install monitor systems in the electron beamline itself as well as provide access to the coherent THz pulses and to femtosecond laser systems clocked to the respective master-clock of the photoinjector.

The common goals shared between ps-fs electron beams (ST3) and plasma accelerators (ST4) will be exploited in SINBAD (“Short INnovative Bunches and Accelerators at DORIS”). This project will start at DESY during the PoF-III period (using major investment funding) in close collaboration between the partners in the ARD ST3 and ST4 research programme. It aims at pushing the bunch length limit to one fs and below and will include experiments for matched injection of such bunches into laser-driven plasma wakefields with the challenging goal of producing stable and high quality, high energy usable beams. In addition, it is foreseen to set up the AXSIS project in the SINBAD facility. AXSIS aims to extend the frontier of short electron bunches into the atto-second regime. A very innovative and compact radiation source will be installed and tested, including THz laser drivers, medical X-band technology, dielectric structures and nano-emitter cathodes. The bundling of these projects together with innovative laser and synchronization technology in a common test facility will provide a large amount of synergy and fruitful cooperation between different activities in the ARD programme topic.

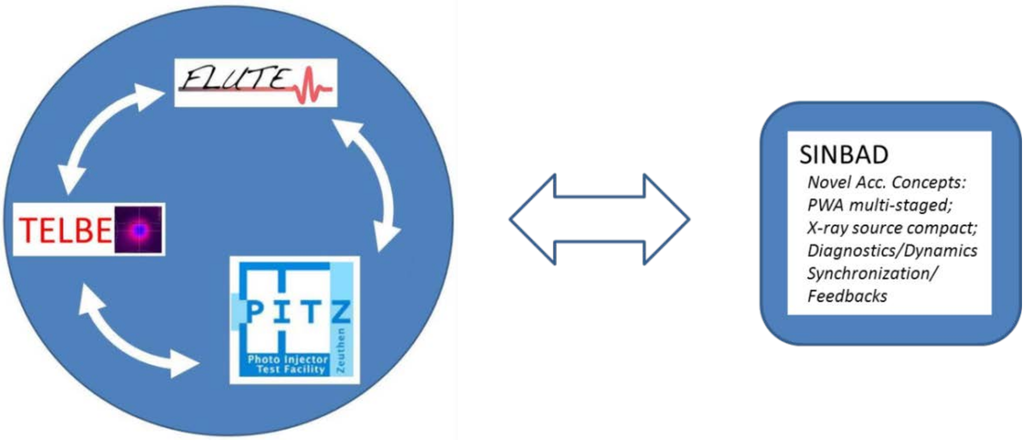

Figure 13: Test facilities for ps-fs low energy electron diagnostic to be established within ST3. FLUTE- test facility for single shot diagnostic, TELBE - test facility for diagnostic on quasi-cw electron beams and PITZ – test facility for electron beams in burst mode. SINBAD for future R&D on novel accelerators concepts.

Besides the above mentioned synergies with ST4, the ST3 activities are also linked to the superconducting RF technology developments in ST1. The narrow bandwidth of s.c. cavities and large stored energy allows to precisely control the accelerating fields through RF feedbacks. The precision field control, however, is fundamental for the stabilization of ps-fs electron beams. A significant fraction of the Subtopic 3 programme relates to investigate, to evaluate and to push the technical limits on the precision RF controls at ELBE, B*ERL*inPro, FLASH and XFEL facilities, thus fostering the developments in superconducting RF technology.

3.1.3.2 Current activities and previous work

Beam dynamics and photon sources

The field of beam dynamics and the development of photon sources is very rich and actively pursued in all of the participating Helmholtz centres. Many collaborations are already in place within the Helmholtz Association but also with external partners. In the following, the activities relevant to the research programme in subtopic 3 are briefly described.

Beam dynamics can become quite particular for short bunches in both linear and ring accelerators. For example, the micro-bunching instability can occur in the bunch compressor of a linear accelerator as well as in short bunch operation of a storage ring light source.

Short bunches in linear accelerators: In the past years very significant progress has been achieved in this field. Linacs such as FLASH, REGAE, PITZ, or ELBE provide bunch lengths or repetition rates over a wide range and the beam dynamics of these short bunches was studied extensively. Due to their high charge densities they experience significant space charge and CSR forces. These processes can be modeled with state-of-the-art simulation tools such as ASTRA and CSRtrack developed at DESY. The steadily improving beam diagnostic tools allow to directly compare the experimental results with simulation predictions. While good agreement was found in many cases, there are still regions in parameter space where the observed dynamics remains unexplained. However, in planning and designing new test facilities such as TELBE and FLUTE the simulation tools play a significant role.

Coherent radiation in storage rings: The Helmholtz Association takes a world leading role in the development of light source operation with reduced ’momentum compacting factor’ (α_c): This operation mode has been pioneered with the BESSY II storage ring. Both the BESSY II and

ANKA light sources offer short bunch length beam in user operation on a regular basis. The MLS storage ring, operated by HZB, is the first machine build with a dedicated scheme for the control of higher order terms of α_c. The beam dynamics activities concerning the phenomenology of short bunches in storage rings are being carried out in an interplay between theory and experiment. The micro-bunching instability, that occurs above a threshold current, is one of the main factors limiting the maximum bunch current and radiation intensity. Since more and more rings are designed worldwide to operate with short bunches (e.g. light sources, but also damping rings for ILC or CLIC) a good understanding and modeling of the instability and the effects influencing it is needed. Making full use of emerging detection technologies significant progress in the mapping of this instability has been achieved in the past few years, an example being the thorough mapping of influencing effects done at the ANKA storage ring.

Custom photon beams

In order to obtain customized beams of photons adapted to the individual needs of user experiments, R&D is ongoing on special shaping of the electron bunches as well as the development of special insertion devices.

Bunch shape manipulation in linear accelerators: A unique and highly flexible photocathode laser system has been employed at PITZ to demonstrate optimum electron beam quality for the standard FLASH and XFEL parameter sets. The system also allows laser pulse shaping to obtain longitudinal electron bunch profiles adapted to specific purposes. A new photocathode laser system now under development for PITZ shall produce quasi 3D ellipsoidal laser pulses, which results in 3D ellipsoidal electron bunches with almost linear space charge forces and substantially reduced slice emittance. The temporal evolution of the coherently emitted electric field pulse from electron bunches is directly affected by a particular bunch shape. A desired electric field pulse shape (e.g. single cycle or multi-cycle, or controlled sequence of ‘half’ cycles) is therefore achieved by appropriate shaping of the longitudinal charge distribution. For the design studies of FLUTE, a programme to efficiently calculate the electric field pulse from arbitrary charge distributions was developed. An extensive experimental programme has been started at TELBE for the study of bunch shape and THz radiation emission and to further develop frequency domain electron beam diagnostics for quasi-cw sources.

Bunch shape manipulation in circular accelerators: Achieving extremely short photon pulses in the X-ray range in storage ring light sources was successfully demonstrated at BESSY II by employing electron bunch femto slicing. Coherent XUV radiation was produced by coherent harmonic generation at DELTA. Both techniques work by using laser-beam interaction to induce sufficiently short and pronounced substructures on the electron bunch. On a different timescale, a variation of geometric impedance interacting with the bunch will also change the bunch shape, thus providing a means to control and tailor coherent THz radiation in storage rings, as has been demonstrated at ANKA. Due to the development of appropriate beam diagnostics, such as fast THz detectors and single shot profile techniques, the dynamics of the modulated electron bunches could be studied experimentally and compared to theory for all cases.

Development of advanced photon sources: A key instrument for high intensity photon beams are insertion devices. At HZB and KIT a comprehensive study programme for the use and development of new materials and concepts is under way. For example at HZB cryogenic permanent magnet undulators based on PrFeB exceeded fields of 1.7 T at 10 K. Tapes of high temperature superconducting (HTS) materials were used at KIT to successfully build prototype undulators. In close collaboration with industry (Babcock Noell GmbH) a HTS mockup was built and its properties measured at the KIT insertion device characterization facility CASPER I.

Ps-fs beam diagnostics

Progress in the short pulse diagnostic area has also been substantial. Meanwhile several novel methods have been tested to determine arrival time and/or pulse duration of THz or X-ray pulses on few femtosecond timescales at the FLASH linac at DESY in a multi-institutional collaboration involving DESY, HJ and HZDR. Some of these results have been published in major interdisciplinary journals proving the leading role of the Helmholtz centres in this crucial subject. In the following the most important current activities are outlined.

Ongoing R&D work in the **time domain** for both **electron** and **photon** beams includes:

Bunch profiling and arrival measurement techniques using EO monitors: Electro-optical crystals can be used to imprint the longitudinal bunch profile into a laser beam which then is diagnosed by standard techniques. A recent success has been the direct electro-optical detection of bunch wake fields in a storage ring (ANKA), allowing for the first time to study the bunch shape variation during the limiting instability with single shot capability (at an acquisition rate of presently about 8 Hz). EO-techniques have also been used for arrival time measurements. At ELBE, this was accomplished on extremely low charged electron bunches (down to the sub-pC level) in quasi-cw accelerators. At FLASH, few femtosecond level arrival times measurements were carried out.

Transverse deflection structure: Transverse deflecting structures are in operation since many years at FLASH. Temporal resolved tomographic bunch studies were successfully carried out which improved substantially the complex beam dynamics understanding at FLASH. Time resolutions below 10 fs were demonstrated and great efforts are made to allow for parasitic operation in user mode.

THz streaking using different sources: X-ray/XUV pulse analysis has also made tremendous progress in the past years. A THz field-driven XUV streak camera based on intrinsically synchronized THz pulses from a THz undulator and more recently using THz fields generated by fs lasers has been tested at FLASH, allowing for sub 10 fs resolution for the determination of the XUV pulse duration and (in the latter case) arrival time.

Fast THz detectors: Detector systems based on a superconducting ultra-fast bolometer with an intrinsic response times in the sub 100 ps timescale to resolve radiation from single bunches have been developed at KIT. A NbN bolometer based detector embedded into a planar log-spiral antenna covers the spectral range from 10 to 150 cm^{-1} (0.3 to 4.5 THz). Even faster response times have been demonstrated with a system based on the high-temperature superconductor $YBa_2Cu_3O_7$-δ (YBCO).

In the **frequency domain,** the development of a unique single-shot THz spectrometry based on diffractive gratings is noteworthy. This has been turned into routine instrument for non-destructive diagnostics on the longitudinal electron bunch form at FLASH. Through parallel readout channels the spectrum of the coherent radiation of an electron bunch is sampled allowing online reconstruction of the bunch shape with high precision (few fs) and high repetition rates (~MHz).

Stability, Control and Synchronization

The peak current and arrival time stability after compression is determined by the amplitude and phase stability of the longitudinal chirp-inducing accelerator section. To meet the stability goals for ps-fs electron bunches, ground-breaking technology developments on the distribution of synchronization signals, the monitoring of arrival times, the RF accelerating field controls and application of fast beam-based feedbacks have already been achieved.

Synchronization: Since long distance RF distribution systems suffer uncontrollable drifts, optical synchronization techniques have been deployed. FLASH is the first accelerator where an optical synchronization system based on the distribution of mode-locked lasers pulses in length stabilized optical fibers links has been implemented. New methods have been invented to measure the bunch arrival time in the accelerator, to generate ultra-low noise microwave signals for the accelerator field controls and to tightly lock ultra-fast laser systems to the optical reference.

This rather young discipline, compared to well establish RF technologies, suffers in achieving the high demands on reliability and operability required by accelerator facilities. Therefore, it is a tremendous achievement that in the meanwhile 10 optically synchronized end-stations are in routine operation at FLASH. Moreover, the bunch arrival time monitors became a standard diagnostic tool for machine operation and accelerator R&D. Through fast intra-train beam based feedbacks the bunch arrival time was recently improved to 12 fs rms, corresponding to about 4µm only, a new world record in FELs and unique selling point for the SRF technology. The FLASH engineered design of the optical synchronization system has meanwhile been installed at the ELBE accelerator to explore the capabilities of a superconducting CW facility.

RF controls: Backbone for reaching this unrivaled stability at FLASH were numerous advances in the RF control technology. To stabilize the accelerating fields with high precision, low-noise field detectors have been developed. Nowadays, these field detectors reach resolutions well below 0.005deg in phase and 0.005% in amplitude. The detected field errors are corrected by fast digital feedbacks. The dramatically increased resource capabilities of today available in Field Programmable Gate Arrays (FPGAs), permit to realize even very sophisticated controllers at low latency. Digital signal processing implemented on FPGAs opens a wide range of new capabilities. It became a key-technology for signal conditioning, automated parameter optimized, iterative learning algorithm, instant beam load correction and is indispensable for fast beam-based feedback adaptations. DESY is meanwhile one of the world leading institutes on the development of RF controls where beam energy stability below 0.005% were demonstrated at FLASH, about a factor of 5 to 10 better than in other facilities. Currently the development is applied to CW superconducting operation and to normal conducting cavities with short RF pulses where fast-feedbacks on the microsecond scale become increasingly difficult to apply.

Control system advances: To meet the high performance goals of future linear accelerators, storage rings and detectors for user experiments, DESY has developed and introduced a new modern electronic standard, called MicroTCA. MicroTCA, or MTCA.4, is based on the Telecommunication Computing Architecture and was adopted by an international interest group from industry and research institutions to the needs for large scale research facilities. Experiences gained so far with the new crate standard have exceeded our expectations. Beside the large communication bandwidth, it was demonstrated, that even very sensitive analog signals e.g. for the RF controls, beam diagnostics and instrumentation, requiring low noise, cutting-edge electronics is crate integrable, impossible, for example, with the 30 years old VME standard. MTCA has built-in redundancy and crate management, essential for achieving high availability in complex accelerators. Through its modular architecture, tailoring of the controls front-end electronics to the particular facility needs, it allows for excellent performance-cost ratio.

Currently the Free Electron Laser FLASH, the photo-injector test facility in Zeuthen PITZ, and several SRF module test-facilities (CMTB, AMTF) are being equipped with MTCA. Within the Subtopic ST3 and the Helmholtz Validation Fund “MTCA.4 for Industry”, HVF-0016, critical subsystems for the test accelerator FLUTE, LLRF tests for CW operation at ELBE and others are planned. High speed cameras with frame rates of several 100000 pictures per second for beam diagnostics and laser stabilization, or 40GHz analog bandwidth ADCs to access storage ring dynamics are just two examples of a strong collaborative effort among the Helmholtz centres with overlap to the second topic in the programme MaT, “Detector Technologies and Systems (DTS)”.

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[2] ‘FLUTE: A versatile linac-based THz source’, M. J. Nasse, M. Schuh, S. Naknaimueang, M. Schwarz, A. Plech, Y.-L. Mathis, R. Rossmanith, P. Wesolowski, E. Huttel, M. Schmelling, A.-S. Müller, Review of Scientific Instruments 84 (2013) 022705–022705–4

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3.1.3.3 Objectives

Beam Dynamics and Photon Sources

The main objectives in the field of beam dynamics and photon sources are concerned (1) with addressing the above mentioned challenges of instabilities caused by the high electro-magnetic fields generated by short electron bunches themselves - a limitation for both linear and circular accelerators - and (2) the generation of photon beams tailored to the needs of next generation experiments.

A major foundation of the proposed research programme proposed is the basic research in the field of the complex nonlinear dynamics and instabilities of extremely short electron bunches in linear and circular accelerators. The studies aim at improved control of the bunch shape and thus of the properties of the generated photon pulse. A definite asset is the possibility to perform experiments at the different test facilities available for the ST3 research mentioned earlier. This allows in a unique way to isolate questions of the underlying physics from hardware considerations. The central aspects of the planned studies are addressed in two partially overlapping categories which are outlined in the following.

Short bunches in linear accelerators: In this context, the focus is on feasibility studies for special beams in linacs. The possibility of THz radiation generated with temporal patterns suitable for pump-probe experiments at the XFEL will be evaluated (PITZ), the production of super-radiant THz radiation in a low-energy quasi-cw linac will be verified (TELBE), the generation of fs electron beams with moderate current will be investigated (FLUTE). The set-up of the new test facility SINBAD will be started using buildings and technical infrastructure of the former DORIS facility with one objective being the generation of very short and stable bunches from a 100 – 150 MeV linac. Furthermore, the AXSIS experiment (cooperation of DESY-CFEL with MIT and SLAC) for the formation of low charge attosecond bunchlets and compact X-ray generation will be linked to the SINBAD facility.

The beam dynamics and stability issues arising in the compression to short bunch length (e.g. influence of space charge and CSR, impedances, evolution of energy spread, RF jitter, etc.) will be studied in unprecedented detail and precision in simulations and bench-marked with appropriate experiments making use of the newly developed high resolution beam diagnostics (see below).

Coherent radiation in storage rings: This project focuses on measures to improve the operation of storage ring light sources with short bunches. An effort will be made to complete the inventory of effects influencing the instability limiting the current of a short bunch in a storage ring. Appropriate simulation codes will be developed and applied to the case of different accelerators where bench-mark experiments will be performed (BESSY II, MLS, ANKA). Also the influence and evolution of wake fields and the heat deposition in the beam vacuum chamber and other structures, e.g. from beam diagnostics installations will be investigated. For the experimental study of energy deposition issues, e.g. the COLDDIAG installation is available. Furthermore, the complex beam dynamics arising from the simultaneous operation with long and short bunches as proposed for BESSY^{VSR} will be studied in detail.

Several approaches are being pursued to generate **custom photon beams** for special experimental use. The projects will be carried out in the following categories:

Bunch shape manipulation in linear accelerators: Since the characteristics of the emitted photon pulse depends largely on the longitudinal charge distribution, different techniques will be employed to effect a modulation of the bunch shape. Approaches under study include the knocking-out of phase space areas in a dispersive section (FLUTE), a modulation on the electron pulse right from the photo injector mediated by a modulation of the injector laser pulse (PITZ, TELBE), the generation of highly compressible elliptical beams by controlling the injector laser pulse (PITZ), the creation of low charge attosecond bunchlets (AXSIS) and the use of a specially designed beam environment to achieve a bunch shape manipulation from wake field interactions.

A central issue is hereby the understanding and control of the emitted photon pulse. For the X-ray case this is straight forward, for long wavelength radiation, the emphasis is on the production of single cycle or multi cycle pulses of arbitrary lengths. A fast simulation code will be developed (e.g. making use of genetic algorithms and modern computing techniques in combination with odes such as ASTRA/CSRtrack) with the photon pulse shape as figure of merit. Another, related field of study concerns the manipulation of transverse phase space to obtain ultimate brilliance beams. The three-dimensional control of the phase space shall allow the generation of high brightness, ultra-small photon beams on attosecond timescales (PITZ, XFEL).

Bunch shape manipulation in circular accelerators: In circular accelerators, the interaction of electro-magnetic fields with the electron bunch will be used to modify and control the bunch shape. In the micro-bunching instability, dynamic substructures appear on the bunch. The feasibility of the stabilization of these short structures, emitting intense coherent THz radiation, by the application of a microwave field to the beam will be investigated (ANKA). A laser-induced modulation will allow the generation of coherent short wavelength (above VUV) radiation with the proposed experiments of echo enabled harmonic generation, EEHG (DELTA/FZJ).

Development of advanced photon sources: Both long and short photon pulses will be generated simultaneously by the application of strong RF focusing to the beam (BESSY^{VSR}). The mutual influence of cavity fields and beam will be studied in detailed simulations and also experimentally. Electron beams with very low emittance (below 1 mm mrad) with repetition rates typical for circular accelerators and bunch lengths of the order typical for linear accelerators will be generated in B*ERL*inPro. An important subject of research is the study of bunch compression down to the 100 fs scale in an ERL facility for a wide range of bunch charges. The achieving of ultra-low emittances in storage rings links the interests of the photon science and high energy physics community. The beam dynamical issues of a CLIC damping wiggler prototype will be addressed experimentally in the ANKA light source. Another important part of this project is the development of special magnets as sources of radiation. Different concepts will be investigated and tested (e.g. in the participating test accelerators), namely novel insertion devices using high temperature taped materials and new IDs based on cryogenic permanent magnets. Due to the close interaction with ST4 a special focus is also on the development of IDs for application in LWFAs.

The beam dynamics and photon source developments will be carried out in close collaboration between the H-centres, international research institutions and university BINP, CERN, IAP, JINR, JLAB, PSI, HU-Berlin, U-Hamburg, and U-Rostock.

ps-fs Electron and Photon Beam Diagnostics

The main objective in the field of ps-fs diagnostics is to keep up with the rapid development of accelerator technology providing femtosecond-level diagnostic for a wide range of beam parameters e.g. for few MeV to GeV beam energies, for charges ranging from pC to nC and for durations from the few femtosecond to few ten picosecond regime. The development of new diagnostic techniques is a major goal within the ARD-ST3 which is approached in a multi-institutional collaborative manner.

Crucial for rapid progress in the development of future ps-fs diagnostic is an easy access to short-pulse accelerators, where the new devices can be installed, commissioned, benchmarked against other methods and finally optimized. Therefore, within ARD-ST3 the following test-bench facilities for the development of diagnostics for ultra-short electron bunches will be established and used jointly for the collaborative research effort: 1.) PITZ at DESY: in burst mode of operation, 2.) FLUTE at KIT: in single-shot mode of operation and 3.) TELBE at HZDR: in quasi-CW mode of operation. Beside the different operation modes, the provided infrastructure differs significantly. Some diagnostic techniques require high power ultrafast laser systems or dedicated specialized photon transport systems. Optimal utilization of the variety of infrastructures available will significantly reduce R&D costs on new and untested techniques before dissemination to other machines.

Although impressive progress has been made, the accurate and robust measurement of the arrival time and duration of electron and photon pulses remains a crucial objective within ARD-ST3. Both properties are addressed by employing two general types of diagnostic working either in the time or frequency domain.

Time Domain Approaches:

Laser-based bunch form monitors: The current drawback of the laser based profiling through electric field probing lies in its relative complexity, insufficient duty cycle and so far limited resolution of 100 fs. Within PoFIII a common design for the e.g. electro-optic monitors at all facilities shall be developed that allows to achieve sub-50 fs resolution for the electron bunch form routinely (e.g. by utilizing a combination of different electro-optic materials). Furthermore this design should be robust enough to allow for 24/7 mode of operation. While the recent developments in femtosecond level diagnostic had originally aimed at linear accelerators it now becomes of high interest for diagnostic on the recently proposed upgrades of storage rings towards few ps electron bunches like BESSY^{VSR} and ANKA where it is required to monitor e.g. the micro-bunching instabilities.

Bunch arrival techniques using EO Monitors: The established techniques based on electro-optic sampling of either the Coulomb field of the electron bunches or the emitted THz pulses now need to be adapted to the different electron beam parameters (low and high charge, few femtosecond – picosecond duration, few Hz and MHz/GHz repetition rates). At CW accelerators such as ELBE/HZDR, the design of electro-optic monitors for the coulomb fields of the electrons shall be optimized to minimize aging of the electro-optic crystals due to interaction with the beam halo. KIT will focus on the development of a single-shot monitor concept that allows routine online analysis of the arrival time on a few femtosecond level down to low charges in the few pC regime.

Arrival techniques using Mach-Zehnder Interferometers (MZI): The highest electron bunch arrival time resolution (6 fs at 200 pC) is achieved by passing broadband electrical signals (~10 GHz) from electron bunch pickups through a Mach-Zehnder Interferometer amplitude modulating optical reference laser pulses at 1550 nm wavelength. The resolution of the method should be further improved by a factor of 100 (<10 fs@1 pC). For facilities without optical reference distribution, the method should be extended to wavelengths at 800 nm and 1060 nm. For the determination of the photon arrival times with high accuracy suited photo-receivers can be used.

Bunch arrival time through phase cavity: Measuring the phase of a narrow band RF cavity exited by an electron bunch is the opposite approach to the MZI method. Temporal resolutions of ~30 fs@20 pC bunch charges have been achieved at LCLS, while currently electronic drifts do not permit the used for feedback applications. By applying low-noise phase measurement techniques, the resolution shall be improved by a factor of 10 (<10 fs @ 10 pC); by including calibration circuitries drifts will be removed.

Frequency Domain Approaches:

Single-shot THz spectrometer: The successful single-shot THz spectrometry concept based on diffractive gratings developed at DESY shall be adapted and transferred to the FLUTE and at a later stage to the TELBE and PITZ facilities. The technology developed at the FLASH linac over the past 10 years allows measuring the emitted coherent THz radiation in a wide frequency range between 0.68 and 54.4 THz with currently available readout times of sub 200 ns. It is thereby very well suited for immediate implementation at FLUTE with its 10 Hz mode of operation. Within PoF-III the readout time shall be improved towards the sub-10 fs timescale to enable access to the THz spectra and thereby a longitudinal distribution within individual electron bunches in quasi – CW 100 kHz beam at TELBE or within the macro-pulse structure at burst mode facilities. While such a frequency domain analysis of the emitted coherent THz amplitude spectra can be performed non-destructively and allows a resolution down to the few femtosecond regime this information is only qualitative since the corresponding phase information is missing. To this end combination with the direct measurements of the electron bunch form by e.g. transverse deflecting cavities or electro-optic techniques have been used to identify fingerprint spectra. While the former is a destructive technique for the electron bunch, the latter can be employed residually either on the electric field of the electron bunch itself or on the emitted THz pulses and holds therefore great promise to be usable alongside the frequency domain monitor.

Compact multi-channel compression monitor: Finally, within PoFIII a compact multichannel THz detector shall be developed to allow a cost efficient upgrade of conventional bunch compression monitors (BCM) with a spectral dimension. The detector shall be based on integrated on-chip GHz to THz antennas that shall be assembled on an area of no more than 3 mm in diameter. Such detector could then replace the presently utilized single element pyro-detectors at conventional BCM stations at FLASH, ELBE, FLUTE and X-FEL. These developments will be carried out in collaboration with university groups with expertise in RF technology and Microwave Photonics.

Additionally, high data rates “universal” DAQ systems suitable for various detectors and camera systems (i.e. ultra-fast streaming electronics or high repetition rate single-shot camera read-out in the MHz range) will be developed for the use in ANKA and FLUTE and then be adapted for use at TELBE, FLASH and PETRA. Also, the development of imaging systems (e.g. for photo injector laser diagnostics but also in the THz range) is foreseen to serve as single-shot feedbacks is of benefit for both linacs and rings.

Collaborating partners on the ps-fs diagnostics R&D are: IAP, JINR, JLAB, PTB, PSI, SLAC, TU-Berlin, U-Bochum, TU-Dortmund, TU-Dresden and U-Hamburg.

Stability, Controls & Synchronization

In this category four activities towards reliable accelerator systems – Synchronization reference, RF Controls, Control system advances and Coherence control XUV seeding – are planned.

Synchronization References:

Pushing the synchronization limits: The limitations of the high performance pulsed optical synchronization system is further pushed from currently about 10 fs towards 1 fs rms stability. Limitation have been identified by polarization mode dispersion, polarization dependent losses, self-phase modulation, as well as systems components that are outside the drift controlling feedback loops. Active and passive stabilization, more robust engineering and higher detection efficiencies are required to overcome the limitations. This research topic would also benefit from the FLUTE test facility upgrades proposed with PICCOLO.

Moderate cost synchronization system: For accelerator facilities spanning large distances (100m – 50 km) with somewhat relaxed synchronization demands, 50 fs or so, more cost efficient and robust solutions than a pulse optical synchronization system are desired. By modulating the RF signals on an optical carrier and applying novel RF calibration techniques precision synchronization links can be realized at moderate costs (<10kEuro/link). The goal of this project is to fully engineer and cost-optimize the new technique for a wide range of accelerator applications.

Through exchange of technology, know-how and personnel, the achievements in the synchronization reference system development will be made available to all ARD test facilities. Precision arrival time controls down to 10-20 fs at FLUTE, PITZ and ELBE are envisioned.

RF controls:

Field detector resolution: Pushing RF field detector resolution to 0.001 deg in phase and 0.001% in amplitude at 1 MHz bandwidth by using improved Local Oscillators (LO) phase noise performance, passive mixer technology and ADCs with lower spectral phase noise density, which might be available in future. To reach such resolutions major improvements on the control of electro-magnetic stray fields and opportunistic currents requiring sophisticated shielding and grounding techniques.

Field detector calibration: Calibration techniques can be applied to remove slow temperature and humidity induced RF cables, RF mixer, local oscillator and clock drifts, as well as faster variations through vibration, electro-magnetic interference and components imperfections. The goal of this project is to develop modular, high performance, compact and cost-efficient solutions controlling the RF drifts to below 10fs peak-to-peak.

RF Feedback bandwidth enhancement: Latency due to the digital feedbacks can limit the applicable bandwidth and thus the achievable stability of the feedback loop. To apply RF feedbacks, e.g. also to very short RF pulses of a few microseconds duration, the high frequency field errors have to be suppressed through a bypassing analog feedback structure. The goal of this development is to achieve feedback bandwidth up to the MHz range where analog and digital feedbacks operate in a complementary frequency range.

The RF control hardware R&D is accomplished by software and firmware developments using modern feedback control theory, efficient filter techniques, and noise suppression algorithm. The implementation may vary from facility to facility due to the different machine requirements, accelerator operation modes, RF power supply chain, and infrastructure or environment condition. Modern, state-of-the-art, RF controls systems pushing the stability limitations are envisioned to be implemented through know-how and technology exchange in all Subtopic 3 involved linear accelerators.

Control system advances:

Through the state-of-the-art crate architecture MTCA.4 the accelerator facilities of the Helmholtz centres will get access to an unrivaled data acquisition and data processing system, improving their controls capability. Dedicated developments are planned e.g. on

- **High speed cameras:** Cameras with user selectable pixel regions (100-10^6 pixel) and variable high-speed rates (1-1000 kHz) provide access to fast profile changes of electron, laser, or photon beams. High speed cameras should be used for direct feedback applications especially to stabilize, control and optimize high average power

laser systems. High speed CCD and CMOS camera systems will be set up in cooperation with the programme topic 3.2 (DTS).
- **Broadband ADCs:** Few 10 picosecond pulses can be characterized by analog ultra-broadband ADCs (~40GHz) and taking multi-samples across the signal pulse. The detector should be designed in FMC (FPGA Mezzanine Carrier) form factor for easy integration to the accelerator controls.

Sharing know-how and experience on firmware and software, the exchange of hardware modules and joint electronics development for accelerator diagnostics, data processing and high-speed actuator drivers through tight collaboration among the ARD-Helmholtz centres is centrepiece of the controls development within ST3.

Coherence control of XUV laser seeding:

To generate user controllable, temporal and spatial fully coherent photon pulses with precisely defined pulse arrival, pulse duration, phase properties and spectral content at short, XUV wavelength is the ultimate goal of the efforts based on laser based seeded CHG and FEL radiation. ARD-ST3 plans to contribute to the developments in this field with the focus on two goals:

EEHG in storage rings: Coherent Harmonic Radiation with high up-conversion efficiency at very short wavelength (<40nm) is planned to be carried out by using Echo-Enabled Harmonic Generation (EEHG) at the storage ring DELTA. This would be the first storage ring demonstrating EEHG. The research programme is targeted to investigate limitations of the novel technique.

Laser phase noise limitation: The spectral phase noise power density scales quadratic with the harmonics up-conversion number N from the optical seed (typically 800nm) to the output XUV wavelength (<10nm). For large harmonics, N=100…1000, the intrinsic laser system phase noise will limit the achievable wavelength by degradation of the longitudinal XUV pulse coherence. The fundamental limits due to the laser phase-noise should be investigated by theory and experimentally, ideally at a seeded FEL, e.g. FLASH or FERMI.

Cooperating partners on the stability, controls and synchronization research developments are: NCBJ, TU-Dortmund, U-Hamburg, TU-Harburg, TU- Łódź and TU-Warsaw.

Technology transfer and networking

The strong exchange of know-how is inherent in the structure of ARD-ST3. The work foreseen in the three fields of research are closely interconnected. Good examples for this are the use of advanced detection methods for the beam dynamics investigations or the importance of ultra-precise synchronization for the generation of customized photon beams. Another characteristic feature for ARD-ST3 is the technology transfer aspect: techniques and devices developed based on the core competence of one participating partner will be available and used in all accelerators participating in the physics and development programme. On the other hand, this provides the developing group with a multitude of testing possibilities with wide parameter ranges. This synergy will lead to a homogenization and facilitate a resource efficient standardization of accelerator technology.

The close collaboration between the ARD-ST3 partners naturally leads to an extension of the already forming network between Helmholtz centres. This environment provides young researchers and students with unique access to the full research infrastructure landscape. The additionally envisaged exchange of personnel will on the one hand allow to build a broad knowledge base across the partner institutions and on the other hand facilitate the work flow of the ARD-ST3 research programme.

The already practiced and very successful series of annual meetings will be continued and complemented by training opportunities. In detail, the planned activities encompass

- annual ARD-ST3 workshops with topical satellite workshops on MTCA developments, EO methods, high resolution bunch profile measurements, high data throughput methods and ultra-stable beams

- hands-on training, for example in short bunch operation, data handling, simulation and the use of advanced diagnostics techniques and methods provided at the participating test facilities on a regular basis
- additionally cross-topic workshops with the programme topic 3.2 Detector Technologies and Systems (DTS) are planned

3.1.3.4 Timelines of activities and expected results

Years	Activity/ result	Participants
2015 – 2019	Precise modeling of collective instabilities Goal: Achieving solid understanding and control of the underlying physics process.	DESY, HZB, HZDR, KIT
2017 – 2018	Femtosecond control of longitudinal bunch form. Goals: Emittance improvement by factor of 2 and more; Femtosecond pulse compression;	DESY, HZDR, KIT
2017 – 2019	Beam studies with high charge longitudinal distribution for multi-user operation in circular accelerators. Goals: Achieving control and stable user operation for ultra-short bunches.	HZB, KIT
2015 – 2017	Online femtosecond arrival time diagnostics. Goals: sub-10 fs electron and photon arrival monitors suitable for low charge and high repetition rate.	DESY, HZDR, KIT
2015 – 2018	Online femtosecond bunch profile diagnostics. Goals: sub-10 fs profiling using frequency domain approaches; sub-50 fs with laser based monitor systems.	DESY, HZDR, KIT
2017 – 2018	Integration of high data rate detector systems for precision control of ps-fs high repetition rate accelerators. Goal: Establish high speed 1-dim and 2-dim beam monitoring systems for fast transient phenomena studies.	DESY, HZB, HZDR, KIT
2015 – 2017	Establish modern crate system MTCA.4 for high speed precision controls in accelerator facilities. Goal: Crate systems are in operation and software adapted to specific facility control architecture.	DESY, HZB, HZDR, KIT
2015 – 2018	Establish femtosecond RF controls for normal and superconducting accelerators. Goal: Phase stability long term < 20 fs pk-pk and short term stability < 5 fs rms demonstrated in SRF & NRF.	DESY, HZDR, KIT

2014 – 2018	Optical synchronization with femtosecond accuracy. Goals: Optical synchronization system with 1fs rms stability short term and <5fs pk-pk stability long term;	DESY
2016 – 2019	Seeding at short wavelength at FLASH and DELTA. Goal: Seeding at XUV wavelength established.	DESY, FZJ

3.1.4 Novel Acceleration Concepts

3.1.4.1 Challenges

Particle acceleration in plasmas, driven by either high power laser pulses or relativistic particle bunches is conceived as one of the most promising candidates for novel accelerator concepts. These schemes stand out through unprecedented acceleration gradients that can be sustained in ionized media and that support a drastic reduction in accelerator length as well as extreme peak currents. Pushed by the advent of university-laboratory scale ultra-short pulse lasers and parallel computing techniques over the last decade, the field has advanced rapidly and now reached a critical level, where “ARD” groups in direct connection with established conventional accelerator facilities will help making the next mandatory step: moving from proof-of-principle studies to stable machines suitable for use in demanding applications such as medical therapy and diagnostics, as well as the driving of compact light sources. Advanced plasma targets, driver control, and metrology will be required to meet the conditions for next generation experiments as projected in numerical simulations – and moving this area forward will be the overarching focus. The main research teams involved in this novel activity (at GSI with HI-Jena, HZDR, and DESY) will therefore uniquely combine their long-standing experience in plasma wakefield acceleration and high power laser development with the expertise in developing and running modern accelerator facilities, latest generation light sources and diagnostics, thus merging unique Helmholtz-infrastructures.

Plasma acceleration concepts can be categorized by the particles to be accelerated (electrons vs. ions) and by the plasma driver (laser pulse vs. particle bunch). In all cases the basic mechanism relies on the driver exciting a charge separation, either co-propagating as for the case of plasma wakefield electron acceleration (PWA) or quasi-stationary as for the case of laser ion acceleration (LIA), leading to electric field gradients on the order of atomic field gradients. Within ARD all categories will be studied, allowing for a maximum in synergy within this subtopic but also with subtopic 3, as issues such as fs-beam dynamics, characterization and synchronization are strongly overlapping.

3.1.4.2 Current activities and previous work

Though the present structure of the Helmholtz research groups focusing on experimental work on plasma based particle acceleration has only been developing over the last couple of years, all groups involved in this subtopic have significantly contributed to the rapidly advancing field. Their leading researchers are well known for their expertise since the pioneering experiments in the early 2000s. Furthermore, the demand for larger-scale infrastructure required for further steps of development is well matched to the Helmholtz mission.

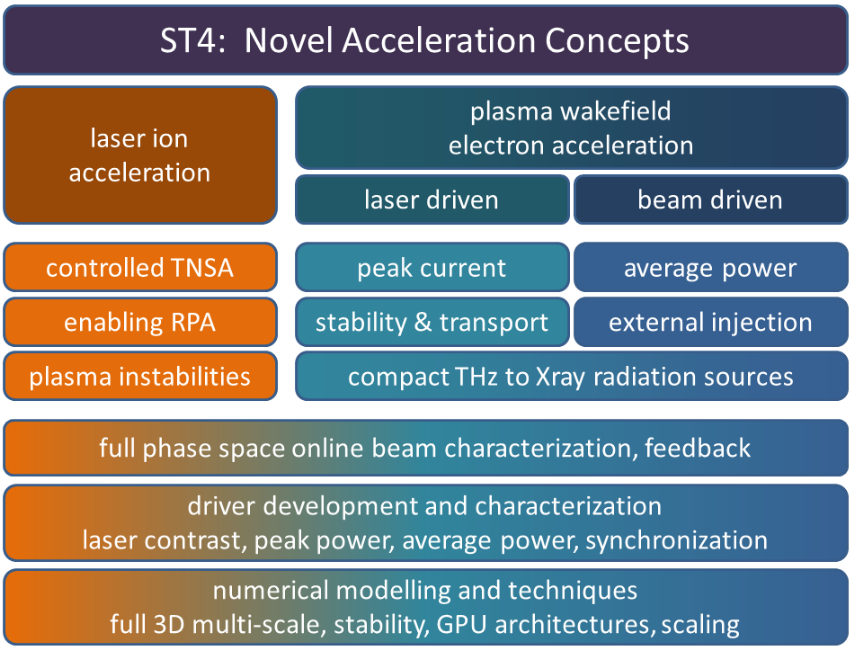

Figure 14 Structure of subtopic 4 highlighting objectives and overarching strategies

In laser ion acceleration (LIA), first experiments producing multi 10 MeV proton emission from thin metal foils used large-scale single-shot lasers. The recent development of table-top, high-repetition rate 100 Terawatt class lasers has opened the possibility for systematic work as well as for first applications. In the robust Target Normal Sheath Acceleration (TNSA) regime, where the thin foil remains opaque to the laser pulse, recent work focused on the understanding of the scaling of the maximum proton energies with laser power (U.Schramm, T. Cowan, HZDR, M. Kaluza, HI-Jena) especially in the hitherto underestimated area of compact ultra-short (<50fs) pulse duration lasers. In this range the role of the non-thermal intra-pulse phase of the acceleration dynamics could be demonstrated (U. Schramm, HZDR) that is partially responsible for a favorable near-linear scaling. These studies culminated in the generation of stable and controlled proton dose delivery to biological samples and proton energies in the range up to 20 MeV, prerequisites for future applications in radio-oncology (U. Schramm, R. Sauerbrey, HZDR), and was accompanied by the development of dedicated online ion metrology.

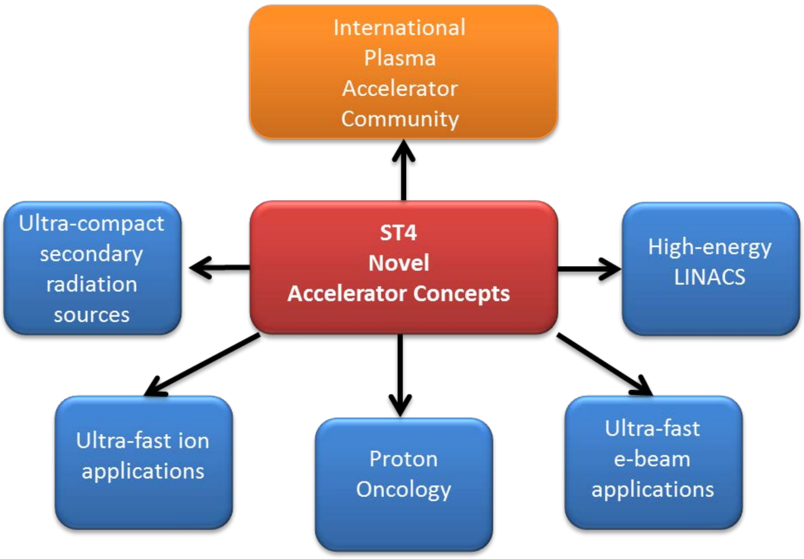

Figure 15: Impact of subtopic 4 on various fields of research

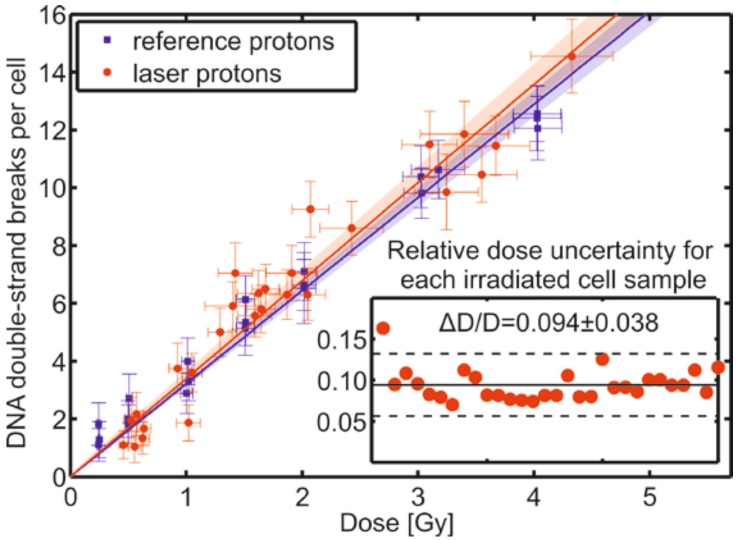

Figure 16: Demonstration of dose stability in laser-driven proton acceleration (inset) for the cancer-research related application of measuring the radio-biological response of irradiated cell-samples

It was found that the acceleration efficiency as well as the spectral shape of the proton pulses can be positively influenced by geometrically confining and by shaping the targets, either by the use of droplets (M. Kaluza, HI-Jena) or of micro-structured targets (T. Cowan, U. Schramm, R. Sauerbrey, HZDR, M. Kaluza, HI-Jena, V. Bagnoud, GSI with TU-Darmstadt), a technique that lead to the at that time highest published proton energies of 67.5 MeV (T. Cowan, HZDR).

Theoretical studies (M. Zepf, HI-Jena) suggested that for higher laser intensities and nm-thin foils a certain degree of transparency will occur. This allows the laser pulse to interact with the foil volume and ultimately for continuous pushing of an electron layer in the radiation pressure regime. Thus a strongly improved performance can be expected for ion spectra and energies. First studies have been performed successfully (M. Zepf, M. Kaluza, V. Bagnoud, HI-Jena and GSI) focusing on the stabilization of the process using high-Z / low-Z target combinations representing an excellent starting point for future work.

Focusing and transport of laser-accelerated particles is a major issue for their preparation for applications, as well as for matching their phase space distribution to conventional accelerator infrastructures. Addressing this task has been started by a collaboration of Helmholtz and university groups (LIGHT collaboration, GSI, HI-Jena, HZDR, TU-Darmstadt, U Fankfurt) with beam collimation studies using pulsed solenoid (T. Cowan, HZDR) and quadrupole lenses at the PHELIX laser (V. Bagnoud, GSI).

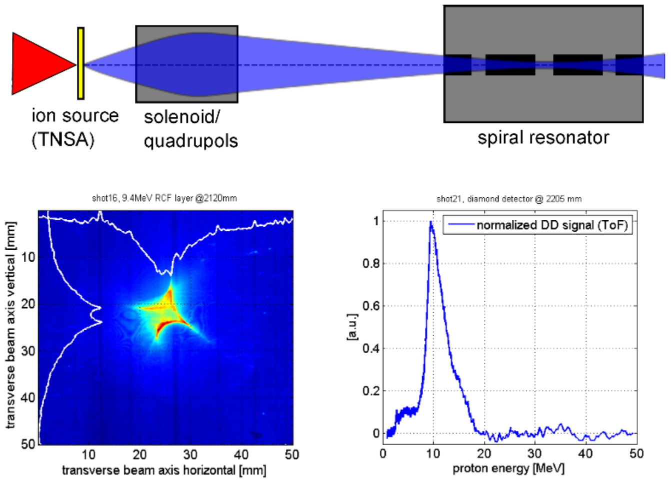

Figure 17: Schematic view of the existing LIGHT beamline combining plasma based and conventional accelerator technology. Bottom: Spatial profile (left) and energy profile (right) of a focused 10 MeV proton beam at 2.2 m behind the laser target.

Though the seminal paper on the principle of Laser Electron Acceleration (LEA) employing plasma waves was published more than 30 years ago, the key breakthrough came 9 years ago, when the non-linear bubble or blow-out laser-wakefield regime was first demonstrated by three independent international groups: LBNL (USA), RAL (U.K.), and LOA (France). Shortly thereafter leading scientists participating in this subtopic reproduced these findings applying additional metrology for, e.g., the measurement of the fs-scale pulse durations (M. Kaluza, HI-Jena, U. Schramm, R. Sauerbrey, HZDR, B. Hidding, UHH) and advanced this emerging field by design studies on PWA-driven Free-Electron Lasers and new undulator concepts (F. Grüner, UHH, U. Schramm, HZDR, M. Kaluza, HI-Jena, A. Bernhard, KIT), and GeV-scale PWA (J. Osterhoff, DESY). Substantial progress has been made in direct observation of the interaction and the acceleration process through ultrafast probing and in determining key interaction parameters such as the bunch diameter and length as well as the emittance (M. Kaluza, HI-Jena, F. Grüner, UHH). First application demonstrations in the field of PWA-based undulator soft X-ray sources based on dedicated electron beam-optics has been reached in a consortium of groups now reforming in this ARD subtopic (F. Grüner, UHH, U. Schramm, HZDR, J. Osterhoff, DESY, M. Kaluza, HI-Jena).

First experiments combining rf-accelerated electron bunches and high power laser pulses have been performed at ELBE (U. Schramm, HZDR, T. Stöhlker, HI-Jena), where in a colliding pulse geometry Thomson scattering has been studied in order to gain an improved understanding on the spectral emission pattern and in order to define the stage for the first combined laser plasma experiments.

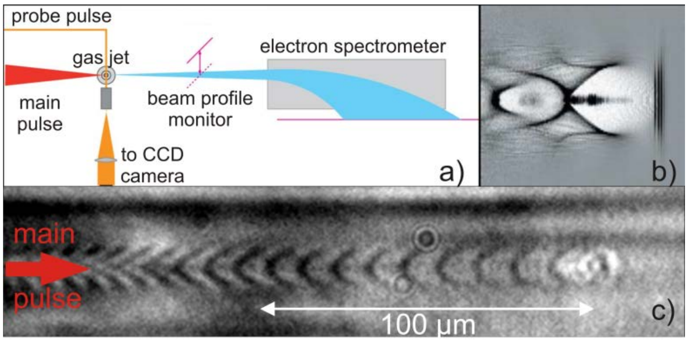

Figure 18: Using a few-cycle optical probe pulse the generation and evolution of a laser-driven plasma can be monitored with fs-temporal and µm-spatial resolution. Using the JETI laser system at HI-Jena with a synchronized 5.9-fs probe pulse (a) images with unprecedented resolution could be obtained (c) showing details of the plasma wave structure which so far were only seen in numerical simulations (b, from Faure et al., Nature (2004)).

Dedicated infrastructure

Both in LIA and LEA, major advances are often closely linked to the development of laser technology. The importance of laser power and pulse duration is obvious, but often more subtle properties such as pulse contrast in the case of the irradiation of the thinnest foils for LIA, but also stability or spectral and spatial beam quality as well as beam pointing in LEA can be crucial. It turned out to be inevitable to intimately link the work of experimentalists and laser physicists in order to allow for the feedback necessary for progress in this field, a situation that could be excellently provided by the established Helmholtz centres (GSI with HI-Jena, HZDR, and now also at DESY). Furthermore, the presently upgraded high power laser infrastructure of the centres is ideally matched to the ARD tasks. State-of-the-art 100-TW-class, ultra-short pulse lasers are operated at HI-Jena and HZDR, equipped with versatile experimental infrastructure, and currently being implemented at DESY together with dedicated undulator beamlines, the HZDR system being presently upgraded to unique PW level on target and multi-beam operation. Average power restrictions are in parallel addressed with the development of directly diode laser pumped PW class lasers, online and pioneering at HI-Jena in the 100 TW scale and upcoming at HZDR, and with future highly parallelized fibre laser development at HI-Jena, where coherent combination strategies may open the way to 100 TW pulse power at 100 kW average power.

These systems are complemented by GSIs high energy short pulse laser, offering ideal conditions for single-shot LIA studies and for investigating upgrade pathways to higher repetition rates of high energy lasers.

Unique experimental conditions are available at all Helmholtz centres due to the combination of the laser sources with complementary conventional accelerator infrastructure. At GSI, the Phelix laser is coupled to the UNILAC heavy ion accelerator and secondary beamlines within LIGHT. At HZDR the multi-beam high power laser can be overlaid with pulse compressed electron bunches of ELBE, continuously improved within subtopics 1 and 3. At DESY, unprecedented conditions will be available at the REGAE and PITZ injectors and at the FLASH-accelerator for beam-driven wakefield experiments and later at the currently planned SINBAD branch of the proposed distributed ARD test-facility.

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3.1.4.3 Objectives

While the accelerator structures to be investigated under ST4 all share the plasma medium as a means to achieving the extremely large fields, they can be grouped into 3 broad research fields:

- LIA (**L**aser **I**on **A**ccelerators)
- LEA (**L**aser **E**lectron **A**ccelerators)
- BEA (**B**eam driven **E**lectron **A**ccelerators)

These areas share similar requirements in terms of laser, target, diagnostic development and numerical simulations and the objectives and activities planned for ST4 will be grouped accordingly. Note that these are not rigid delineations and that much of the development related to lasers, targets and numerical simulations has overlaps and synergies between these areas.

Laser Ion Acceleration

In *laser ion acceleration* (LIA) the objective lies in generating ion bunches with exceptional parameters at energies exceeding the 100 MeV range and with an amount of control in spectral and spatial beam quality that can compete with that of conventional sources and allows for demanding applications. This task should, however, not be misunderstood with simply emulating parameters of a conventional accelerator with a more compact source. Instead the focus is to develop an accelerator scheme with unique beam properties that can only be achieved with LIA.

These tasks ask for well-tailored laser parameters at increased intensities, innovative target solutions, both provided for by all contributing Helmholtz centres and full-scale understanding of the interaction dynamics. The programme will be closely coupled between experimental efforts and numerical simulations on advanced computing infrastructure available in Germany and abroad to foster understanding and control of laser ion acceleration. During the PoF-III period there will be ongoing improvement and upgrades to the cutting-edge laser systems in operation at GSI, HI-Jena and HZDR. To control and optimise the microscopic LIA accelerator structures the lasers will be developed further to achieve exceptional pulse contrast, and spatial beam quality. Novel diagnostics to allow advanced single shot metrology of a full suite of pulse-parameters will be provided. This is viewed as essential to pin-point limitations in current lasers systems and to achieve systematic, goal oriented development.

Advancing from the established, of particular interest is the thin foil limit of the TNSA regime, where relativistic induced transparency allows for the interaction with the entire thin foil target volume. This approach has resulted in the highest particle energies observed to date. The three laboratories (GSI, HI-Jena, HZDR) with complementary parameter ranges aim to establish the energy scaling in this regime with respect to laser intensity and target density for maximizing the performance with respect to proton beam parameters.

Radiation Pressure Acceleration (RPA) has shown greatest promise in numerical simulations to date with mono-energetic beams and narrow angular divergence predicted. While first promising signatures have been observed, RPA dominant interactions are yet to be achieved which exploit the rapid scaling with laser intensity to high particle energies. RPA dominant interactions require exceptional control and metrology of the laser parameters – particularly quasi 1D interactions (i.e. top-hat focal spots) and very high laser contrast. This is currently beyond the scope of sufficiently intense lasers and achieving these parameters will be a major focus at all contributing centres.

For all areas of LIA the development of advanced targetry such as microscopic liquid hydrogen targets, nm-scale thin and µm-structured foils plays an important role. For example, targets with structured density profile (such as near-critical to high density transitions on nm-scales) will be investigated with the aim of exploiting the non-linear pulse shaping in the low density region for enhanced performance. For applications where continuous operation is crucial, i.e., medical applications or for LIA-based pump-probe experiments with ions at the future XFEL, the development of target systems capable of automated high-repetition rate operation will be developed. Note that for certain target types as hydrogen droplets this is intrinsically the case.

While direct control of the LIA plasma accelerator structure is one key approach, there is a broad range of technologies available from RF accelerators. We will aim to exploit such established technology to control the characteristics of LIA generated beams. GSI with the LIGHT collaboration is ideally placed to achieve this with their combination of expertise and will drive the injection of LIA beams into RF accelerator structures to control the beam parameters. A similar, yet more compact approach, followed at HZDR, aims for the combination of LIA injectors with microstructure cavities that will be optically driven with intense long wavelength THz pulses. When generated from LPWA electrons, such a scheme optimally combines use of novel concepts with the compactness of laser driven sources.

An essential part of the programme will be diagnostic developments, such as developing advanced particle beam diagnostics that allow for improved characterization of the ion beam phase space, such as gated 2D detectors capable of resolving multiple energy slices and advanced, time resolved density diagnostic for thin film targets based on probing the target with a HHG spectrum generated by a probe beam and density profile measurements using Frequency-Domain-Interferometry to measure the density gradient with tens of nm resolution.

The work in all these key research fields will be accompanied by first-principle simulations and modeling, which are necessary to advance the predictive capabilities of current LIA models and will drive the development of new target designs, enhanced diagnostic schemes and, ultimately, the optimization of LIA schemes.

Plasma electron acceleration

In plasma-based electron acceleration, the main objective is the simultaneous improvement of key parameters as peak energy and relative energy spread, transverse emittance, bunch duration and charge. Enabling beam transport from the accelerator to an application target or light source, i.e., exiting the plasma region without degradation of the emittance, will be of paramount importance. Further in the future, the achievable total average power of the beams needs to be addressed. Such increased stability will be proven by implementing various applications, starting from pump-probe experiments with PWA-driven THz and soft X-ray undulator radiation, over medical imaging with PWA-based hard X-ray sources, to PWA-driven or PWA-boosted Free-Electron-Laser (FEL) demonstrators. While such installations will not yet qualify for user facilities, their aim is to demonstrate the feasibility of such PWA-based facilities. A key application will be the advancement of medical imaging by pushing the sensitivity frontier to ultra-low diagnostic agent concentrations used in medical research and diagnostic. On the path towards such applications the centres benefit from strong links to subtopic 3 of the topic ARD, the related detector development within this programme M&T, neighboring Helmholtz research fields as health, as well as a number of established international collaborations with leading institutions in the field.

To achieve these goals, two different approaches will be pursued. While in all plasma-based acceleration scenarios a high-amplitude plasma wave is employed to generate the extreme longitudinal electric fields, different drivers for this wave may be used. The plasma wave can either be generated by high-intensity laser pulses (LEA) or by using externally injected particle beams (BEA). It is of paramount importance for both approaches to reach a degree of controllability over the parameters of the electron pulses which has to be preceded by the full understanding of the physics underlying the acceleration process.

Laser-driven Electron Acceleration - LEA

Great progress has been made over the last years in the control of key beam parameters such as energy spread, emittance, and charge by actively influencing the injection phase in the colliding laser pulse scheme, in making use of density ramps or ionization injection. Still, full understanding of these methods beyond the level of proof-of-concept experiments, the capability of optimizing important parameters as peak current for driving secondary sources, and especially beam transport without quality loss deserves further investigations that will be undertaken at all contributing centres.

A complementary route to more stable conditions can be the elimination of the nonlinear laser injection of electrons itself by the injection of well-tailored bunches from dedicated conventional accelerators. External injection studies allow for the measurement of the emittance growth of the injected bunch due to the plasma wakefield, the energy redistribution, and bunch length change and thus for a mapping of the wakefield itself. With sources as REGAE (initial norm. emittance below 0.1 mm·mrad, bunch energy and length 5 MeV and 10 fs), injection into a quasi-linear wakefield of 100µm length can be performed, while the synchronization between the electron bunch and the wakefield excitation laser will be based on the developments in ST3. Such new types of experiments enable the back-calculation of the wakefield structure and thus the benchmarking of numerical modeling. Identifying and quantifying the sources for emittance and energy spread growth will culminate in a significantly increased tailoring and control of the PWA-process – the prerequisite of future applications. Demonstration of external beam injection is also a first crucial step towards multistage PWA-facilities for very high beam energy in a more distant future.

Beam-driven Electron Acceleration - BEA

A complimentary approach mitigating intrinsic drawbacks of LEA such as low average power and complications caused by wakefield dephasing and laser guiding, can be realized by the application of particle-beam drivers. At the FLASH accelerator, the study of BEA will allow for the advancement of novel-accelerator science by exploring external beam injection and in-plasma witness-beam generation at the multi-GeV level. This will be realized through innovative electron-trapping techniques facilitated by plasma targets with tailored plasma-density profiles. These targets consist of Hydrogen-filled channels preionized by a high-intensity laser pulse. Their density distributions can be shaped by a variation of the gas-filling pressures through various inlets along the channel and in addition by adding dopants. In particular, laser-triggered ionization processes will benefit from the excellent laser-to-beam synchronization available at FLASH, which has been demonstrated on a 30 fs level and is likely to improve further. Moreover, the FLASH accelerator offers unique tunability with its versatile beam-shaping features allowing for the creation of driver beams with triangular current profiles, ideal for the realization of transformer ratios of up to six, surpassing the current state-of-the-art value of two.

Studies towards higher transformer ratios up to 8 can also be performed at PITZ with energies as low as 25 MeV, then using a train of bunchlets with linearly increasing charge, followed by one lower-charge witness bunch. These experiments are possible due to a photo cathode laser system with unique laser pulse shape capabilities developed by the Max-Born-Institute and installed at PITZ. With the same beam-driven facility an important effect will be examined that can be regarded as a benchmark for the planned CERN-project AWAKE of a proton-driven PWA, that is, the self-modulation of a bunch. The CERN proton driver is much longer than the plasma period, hence no coherent wake can be excited. By self-modulation the driver bunch builds up a density modulation on the scale of the plasma period. This principle will be studied with the electron beam at PITZ. Beam diagnostics needed for those activities will be further developed within subtopic 3.

Joint objectives for LEA and BEA

Since there are a number of similarities for all plasma-based electron acceleration scenarios it is only natural that synergies will emerge. They will be exploited by all contributing ARD ST4 partners. Since the success of all plasma-based electron acceleration approaches heavily relies on the availability of well-tailored plasma targets, their development will be a joint task to be distributed among the contributing centres. Here, special gas-density distributions also including different gas types and the combination with laser- or current-induced preionization of the gas will be further developed. The availability of suitable diagnostic tools both for the driving plasma wave and for the generated particle pulses will be beneficial both for LEA and BEA. In both scenarios, the evolution of the witness beam which is accelerated by either the laser- or beam-driven plasma wave will provide information about the plasma wave's internal field structure. This highly field-sensitive method can be complemented by high-resolution optical probing techniques which additionally provide time- and space-resolved information about the plasma wave's structure and its evolution. Furthermore, specifically designed undulator structures, well-adapted to electron pulses exhibiting relatively large energy spread of a few percent will be employed to measure primary bunch parameters such as its transverse emittance or its internal charge distribution. Tests concerning the stability of the particle pulses generated via LEA or BEA e.g. employing pump-probe experiments with secondary radiation generated by these particle pulses will be carried out to characterize and further improve the shot-to-shot stability. These tests can also serve as proof-of-principle studies for staging several PWA-units towards higher output energies and for further application of these particle pulses, e.g. for medically relevant radiation sources or for FEL-operation. Once suitable online diagnostics for the generated particle pulses are available they can be directly linked to online diagnostics for the plasma driver and automatic, real-time data analysis. The ultimate goal will be the development of closed-loop systems to actively stabilize the electron beam parameters as they are already available for conventional accelerators. To understand and ultimately harness most of the phenomena underlying the acceleration process, numerical simulations will be of vital importance. Here, the generation and the transport of the particle beams together with their subsequent interaction with a plasma target and the ultimate generation of secondary radiation need to be understood as precisely as possible in order to push plasma-based electron acceleration beyond its current limits. This will be achieved by carrying out multi-scale, multi-physics numerical simulations at the contributing ARD partners. Last but not least, a number of multi-beam pump-probe experiments, which are planned for the future European XFEL, will strongly benefit from all results achieved in this subtopic.

SINBAD Contributions to the ARD Test Facility

The aforementioned electron acceleration activities can be considered as part of a broad route into one branch of a distributed ARD test facility as envisioned in the Helmholtz Road Map (for the wider scope, see also Section 3.1). We foresee the implementation of a sustainable and future-proof research field in which most priority research projects on plasma-based electron acceleration mentioned above can be combined. In a first step, complementing the existing and future facilities at GSI, HIJ, and HZDR, DESY plans to provide a conventional 100-MeV-Linac at the planned SINBAD-facility for extending laser-driven PWA external injection studies from low energy and charge at the REGAE electron-gun (5 MeV, sub-pC charge) to high energies and charges (100 MeV, few ten pC), where the external electron velocities are about to match with the wake's phase velocity. SINBAD will be hosted in the DORIS hall, a former synchrotron facility at DESY. Its adjacent space is ideal for X-ray experiments aiming at very high stability, based on the conventional linac as the injector and pre-accelerator for the subsequent PWA-stage. SINBAD's substantially larger lab space will allow detailed studies of the extraction, matching, and transport of PWA-bunches over long beamlines without emittance degradation. The necessary synchronization between the linac and the laser will be adopted from the achievements at REGAE with its low energies mentioned above. The linac technology can be based on the AXSIS-project described in subtopic 3. The AXSIS bunches with small emittances and duration of much below 1 fs would allow for studies of high quality beam acceleration in high plasma densities.

Next Generation Laser Development

It is clear from the objectives that for LIA and LEA lasers and their precise pulse parameters play a central role in realizing plasma based accelerators. The control of laser performance and parameters is therefore crucial to meeting the overall challenge of realizing ultra-compact particle accelerators with exceptional beam parameters. Much of the focus in the objectives has been in controlling the spatio-temporal distribution of individual pulses to achieve control of the plasma accelerator structure. For the current developmental phase of plasma based accelerators laser technology based on individual components provides the flexibility and upgradeability required to test new concepts in a flexible manner. The lasers presently available cover the range of current cutting edge laser technology world-wide for lasers in the multi-100 TW to PW class. The participating centres currently have access to continuously upgraded laser systems forming a platform with unique parameter variability for accelerator development during the following PoF period.

However, once stable high performance systems have been demonstrated, a transition to higher average power systems is essential if the full potential is to be realized. Current lasers (Ti:Sapphire and diode pumped Yb doped media) are scalable to or already achieve repetition rates of the order of 10Hz and average laser power of 0.1 -1 kW resulting in an achievable particle beam power (10-100W) comparable to many conventional accelerators.

Moving beyond this to higher average powers, which are desirable for many applications requires a shift in laser design. Fiber lasers based systems (direct or Optical Parametric Amplification have the potential to reach 10kW. HI-Jena will tackle some of the basic design challenges to en route to achieving this goal such as enhancement cavities and fiber synchronization to allow spatially and temporally multiplexed pulses to form a single high-energy pulses.

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3.1.4.4 Timeline of Activities and Expected Results

Years	Laser Ion acceleration (LIA) Activity/ Result	Participants
2014 - 2016	LIA to energies exceeding 100 MeV / nucleon.	GSI, HI-Jena, HZDR
2014 - 2016	Transport of LIA pulses in dedicated compact structures like pulsed magnets and active phase space manipulation.	GSI, HZDR
2014 - 2017	Investigation of parameter scaling of LIA in TNSA and advanced (induced transparency based) regimes for improving beam parameter control at energy levels above 100 MeV.	GSI, HI-Jena, HZDR
2014 - 2019	Liquid and solid hydrogen targets capable of 10Hz repetition. Targets with structured density profiles in the nm-scale thickness range.	GSI, HI-Jena
2014 - 2019	Development and application of novel algorithms and architectures for 3D simulations of high power laser solid density interactions under realistic conditions	HZDR
2015 - 2016	Preparation of quasi-1D interaction conditions with flat focal energy distributions and ultra-high laser pulse contrast for reaching the RPA regime	HI-Jena, HZDR
2017 – 2019	Investigation of transition from advanced TNSA to RPA regimes	HZDR
2017 - 2019	RPA dominant interaction with quasi-monoenergetic energy distribution (<20%)	HI-Jena
2016 – 2019	Study of multi-beam driven or THz driven multi-stage acceleration of ion pulses	HZDR

Years	Laser Electron Acceleration (LEA) Activity/ result	Participants
2015 – 2017	Generation of intense super-radiant THz pulses for driving micro-structure based ion acceleration and spectroscopy	HZDR
2014 – 2017	Simulations of LEA including radiation effects for studying single- and multi-stage LEA schemes and light source design	HZDR
2015 – 2018	Characterization of LEA-based undulator and Thomson scattering radiation for pump-probe experiments	DESY, HZDR, KIT, UHH
2015 – 2018	Optical probing of high-amplitude plasma waves for LEA vs. BEA with sub plasma-scale resolution (< 10 fs and < 1.5 µm)	DESY,HI-Jena, (HZDR)
2016	Online characterization of specifically tailored underdense plasma targets (densities 1×10^{17} cm^{-3} $\leq n_e \leq 5\times10^{19}$ cm^{-3})	DESY, HI-Jena, UHH

2016 - 2019	Development of online-diagnostics for electron bunches (charge, bunch duration, emittance) and laser parameters suitable for active feed-back loops	DESY, HI-Jena, HZDR, KIT, UHH
2014 - 2016	Exploratory studies with external injection at low-energy (5 MeV) and low-charge (sub-pC) for mapping laser-driven wakefields	DESY, UHH
2015 - 2019	Studies on medical imaging of diagnostic agents with LEA electron source for Thomson backscattering for up to few hundred keV photons	DESY,UHH
2016- 2019	Optimization of LEA, plasma extraction, beam transport, and undulator technology (cryogenic and super-conducting) for a free-electron laser (FEL) demonstrator (gain of one order of magnitude)	DESY, HI-Jena, HZB, KIT, UHH

Years	**Beam Driven Electron Acceleration (BEA)**	**Participants**
2016 – 2019	BEA studies for GeV-energy external injection and plasma booster, plasma-boosted FEL demonstrator, bunch diagnostics	DESY, HI-Jena, UHH
2016 – 2019	Setup of 100-MeV-Linac and re-allocation of beamlines to SINBAD, advancing external injection studies to higher energy (100 MeV) and charge (few 10 pc), staging of two PWA-cells, setting up linac-based, PWA-boosted light sources	DESY, HI-Jena, HZB, KIT, UHH
2014 – 2017	Studies on beam self-modulation and high transformer ratios	DESY, UHH

Years	**Next Generation Laser Development**	**Participants**
2015 – 2018	Development of contrast-enhancement modules for PW class lasers based on double-CPA to achieve relative ASE intensity contrast < 10^{-11} @ $t \leq -20$ ps	HI-Jena, HZDR, GSI
2016 – 2019	Development of advanced cooling techniques for high-rep rate, diode pumped PW laser amplifiers	HI-Jena, HZDR
2017 - 2019	Development of novel fiber based high repetition rate laser concepts targeting >1J pulse energy, <300fs pulse duration at >10kHz repetition rate	HI-Jena

3.2 Detector Technology and Systems

The science goals of the Research Field “Matter” range from understanding the generation of fundamental particle masses, the matter-antimatter asymmetry in the universe, and the nature of Dark Matter to the analysis and modification of the structure, dynamics and function of matter and materials.

Scientific advances in “Matter” rely on the successful design and operation of large-scale infrastructures including astroparticle observatories, particle accelerators, light, ion and neutron sources. Prominent examples of current and planned facilities together with their anticipated dates of construction, operation or upgrades are compiled in Figure 20. In order to maximize the science yield, these facilities need to be complemented by powerful and sophisticated detector systems.

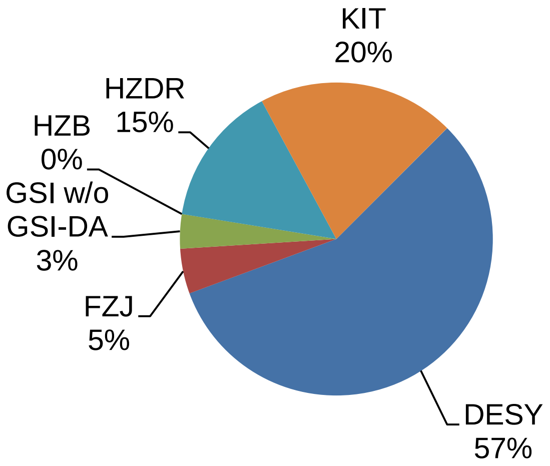

Figure 19: Distribution of resources in the programme topic DTS according to centre.

The detector requirements are driven by the science of the research field “Matter”. The ever-increasing performance of modern accelerators and sources in terms of brilliance, intensity, energy resolution, beam energy, time structure and the like lead to remarkable technical challenges (see Figure 21) and extreme experimental and environmental conditions. This makes the detectors of “Matter” unique and complex.

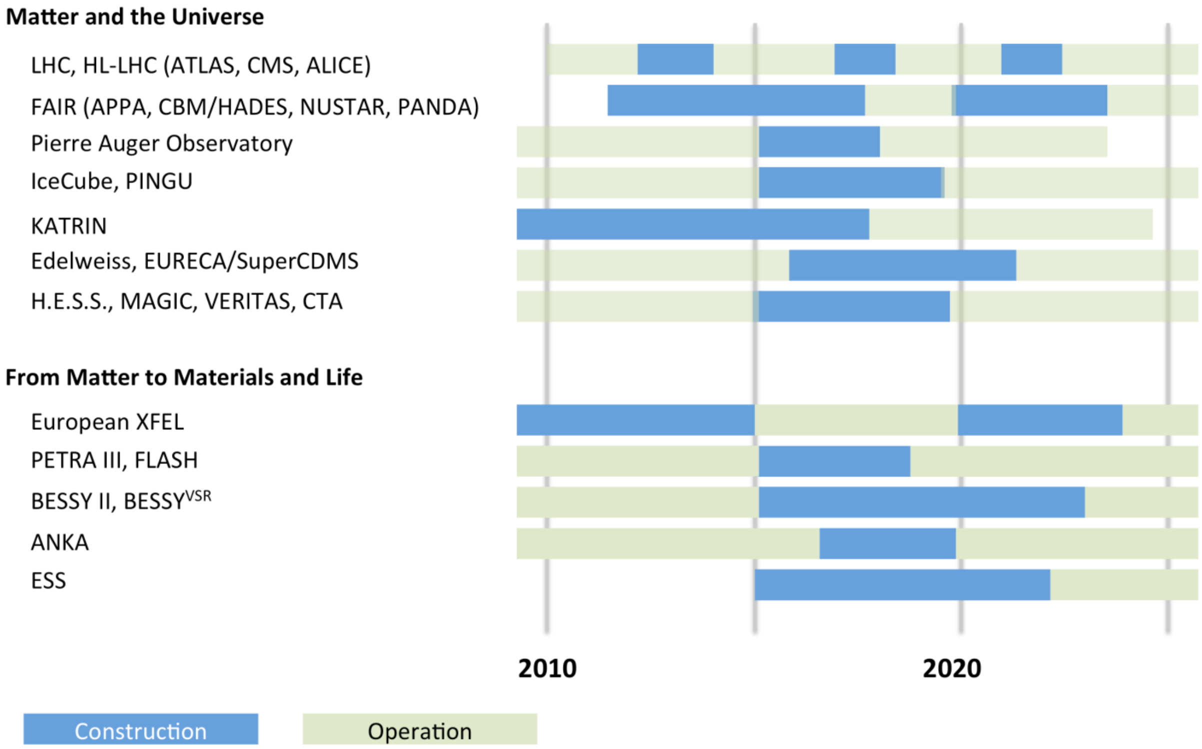

Figure 20: Some current and planned large scale facilities of “Matter” with particular relevance to this programme topic. (In some cases operation of the facility is being continued during construction, extention or upgrade periods.)

Often, progress in detector performance is furthered by technological advances in e.g. the microelectronics industry and materials sciences. Finally novel detector types are made possible through conceptual breakthroughs.

For detector instrumentation in "Matter", commercial off-the-shelf solutions are frequently found to be inadequate. Instead dedicated research and development by hundreds of scientists and engineers over many years is essential before even the technical feasibility of the required detector system, and thus its science reach, can be firmly established. Successful detector instrumentation requires a deep understanding of the underlying physics principles, technological expertise, access to sophisticated and expensive technological processes, and the experience to combine these into complex functional detector systems. With the ever-increasing scientific and technological challenges, it is crucial to exploit the huge synergies between fields and Centres and to collaborate on a national and international scale.

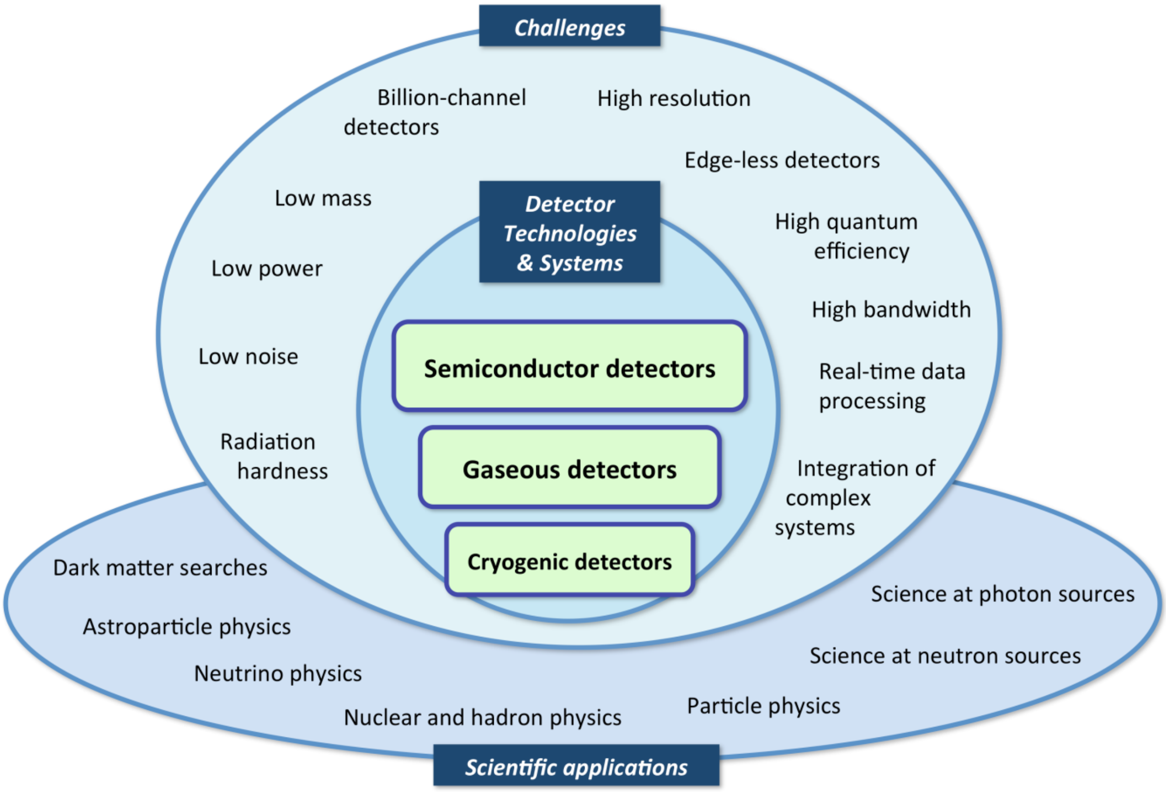

Figure 21: Scientific applications and detector types of DTS

Thus the Helmholtz Centres of the research field "Matter" decided to create the "Platform for Detector Technologies and Systems", a consortium of all the Helmholtz centres of the research field, various international research councils and university groups. The proposal was submitted in 2011, evaluated by external referees and approved by the Helmholtz Senate in October 2011. The approved funding for the platform within 2012-2014 is 7 M€. The platform is now being continued as a Helmholtz programme topic within "Matter and Technology". The proposed breakdown of resources for the topic is shown in Figure 19. The programme topic is an essential element of the research strategy of "Matter" as outlined in the Position Paper of the research field and is fully aligned with the Helmholtz Mission. It puts the level of cooperation between the participating Helmholtz centres and partners to an unprecedented level.

The programme topic "Detector Technologies and Systems (DTS)" will develop and secure access to key technologies, design and build cutting-edge detector demonstrator systems, advance detector instrumentation at large and thus help ensure the scientific competiveness of "Matter". The programme topic reflects the long-term nature of detector R&D and addresses the rising costs of critical technologies e.g. microelectronics. It is an ambitious and probably unique attempt to exploit synergies not only across many centres but also across a wide range of scientific applications.

Each of the participating centres has a strong history in detector instrumentation and a demonstrated record of successfully exploring innovative detector technologies and concepts and, last but not least, delivering cutting-edge detector systems to big science experiments. The combined expertise of the scientists, engineers and technicians contributing to the programme topic extends to technologies and detector systems for particle and astroparticle physics, hadron and nuclear physics, photon science and more. Many of the participants have been involved in all phases of detector development from conceptual design, technology exploration, research and development to detector mass production and commissioning. They have developed the underpinning technologies and have been delivering detectors that are either operational or being built-up. This includes detectors placed at the large-scales facilities at the participating Centres (e.g. CBM, KATRIN, PANDA or the PETRA III and X-FEL detectors) or elsewhere (e.g. the detectors for the LHC, HL-LHC, Pierre-Auger Observatory, and Cherenkov Telescope Array). Most of the principal investigators have been holding or hold leadership positions in international collaborations. A particular characteristic of the participating centres is the significant fraction of experienced engineers and technicians next to the scientists and the availability of technical infrastructure for the integration of complete systems and high-precision assemblies.

DTS will develop and explore enabling technologies, prove concepts by assembly and characterization of detector demonstrators and demonstrate the scalability of detector systems. The experiment-specific mass production, large-scale detector integration, commissioning and operation remain the responsibility of the large experimental groups in the programmes “Matter and the Universe” and “From Matter to Materials and Life”. It should be mentioned, however, that a significant fraction of the scientists and engineers in this topic remain well positioned in the (large-scale) collaborations or instrumentation projects of the aforementioned programmes e.g. as detector specialists in the LHC collaborations ATLAS and CMS, the International Linear Collider experiment ILD, the FAIR collaborations CBM and PANDA, the European XFEL projects, etc. This deliberate arrangement ensures that the technologies and systems developed within “Matter and Technology” remain science-driven, that know-how can be transferred smoothly and that excessive “blue-sky research” is avoided. At the same time the synergies mentioned above are fully exploited. We believe that the detector consortium is large and diverse enough to be a major player on the international scene and to be able to pull beyond its weight.

In selecting the focus of our activities, the technologies and detector systems to target, we were guided by the following questions:

- Which are the key technologies to enable the science?
- Investment in which detector types offers the highest science return?
- Where are synergies largest and where is collaboration most rewarding?
- In which areas is DTS already world-leading and where should its technical portfolio be enhanced?

This led us to emphasise technologies for a) highly integrated, pixelated detector systems with millions to billions of channels and for b) detectors producing enormous amounts of data, with data rates ranging from Gigabits/s to Terabits/s or even Petabits/s for larger systems. Neutron detector technology and neutron detectors are developed in the programme “From Matter to Materials and Life”. We believe to have compiled a coherent research portfolio (see Figure 22) that fits to our competences and scientific needs

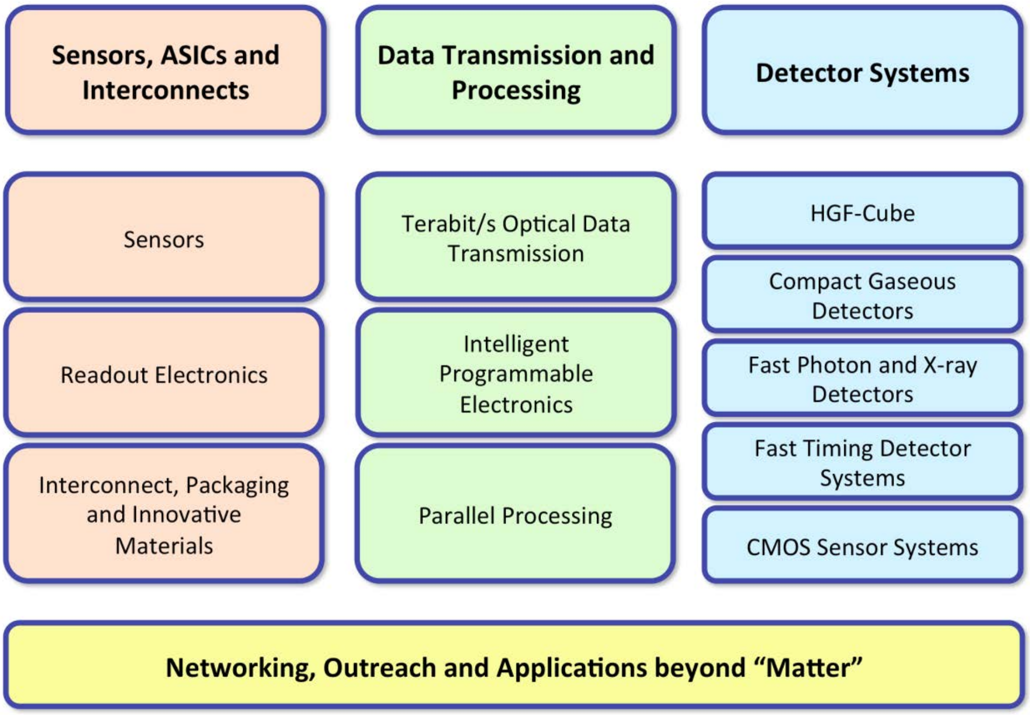

Figure 22: Structure and activities of “Detector Technology and Systems”.

The programme topic “Detector Technology and Systems” is organised in three subtopics. There are numerous cross-links within and between the subtopics. The content of the first two subtopics “Sensors, ASICs and Interconnects” and “Data transmission and processing” are underlying technologies and technological building blocks. A rigorous validation of these technologies is carried through in the third subtopic “Detector Systems” where these building blocks are combined to produce fully functional cutting-edge detector demonstrators. Depending on their scientific purpose, the demonstrators may either be directly used for science at e.g. at the experimental station of a light source or put to test in a particle beam test facility. While the research topics of “Detector Technologies and Systems” are well-defined, and have been structured in implementation steps and milestones, they allow us to accommodate the unexpected and react to opportunities not yet obvious today.

An efficient and lean coordination structure for DTS was set up, based on the experience with the “Platform for Detector Technologies and Systems” which is operating successfully since 2012. It includes an executive board, subtopic coordinators, research activity coordinators, regular coordination meetings and evaluations. The structure is described in more detail in section 2.3.

The topic DTS is well embedded in the international community and collaborates with numerous national and international partner institutions and universities. Already with the foundation of the Platform for Detector Technologies and Systems an advisory board composed of outstanding international scientists was established. A strategic partner of DTS is the Munich Semiconductor Laboratory of the Max Planck Society (HLL MPG). Joint research projects include the development of fast photon and X-ray detectors. The full list of partners is given in section 2.1.2.

DTS has been and will be contributing to the detector-related activities of several Helmholtz alliances, namely “Terascale”, “EMMI” and “HAP” which will combine their community-specific networking activities to form the programme network MuTLink. MuTLink will be a most valuable framework for close interaction and communication with very many German university groups working in the field. High-ranking workshops like the recent Wilhelm and Else Heraeus Seminar on “Development of High-Resolution Pixel Detectors and their Use in Science and Society” are one element of DTS’ networking strategy to systematically expand links to industrial partners.

Detector instrumentation has wide applications in other Research Fields of the Helmholtz Association and in society at large. This is addressed by the activity “Detector Technology and

Society" which aims to (i) raise the visibility of the topic "Detector technologies and systems" beyond "Matter"; (ii) identify applications of detector instrumentation of high societal relevance and further knowledge exchange; and (iii) seek, educate, recruit and promote young talent in the field of detector instrumentation.

Talent management and promotion of young researchers is crucial for almost any research field. Here it may be even more important than elsewhere since our graduate students have acquired skills very much looked for in industry and easily find attractive first employment. The installation of DTS and its predecessor in 2012 has raised the awareness of detector instrumentation within the Helmholtz Association and beyond. Many members of DTS are engaged in teaching and give lectures or courses at universities. Our meetings and workshops are a welcome tool to make young talent visible beyond their home institution. A number of post-doctoral and permanent positions have already been created. In addition, the ASIC design capability within "Matter" has been strengthened further in a concerted effort between centres. DTS members have demonstrated their ability to create strategic positions for outstanding scientists by e.g. establishing a W3-professorship for ASIC Design and Detector Technology. Every effort will be made to continue this promising trend. Particularly efficient mechanisms are the tenure track or multi-track programmes of the Helmholtz centres and the instrument of Helmholtz Young Investigator groups. The number of female researchers in detector instrumentation is deplorably low in Germany. It is critical for the future of the field to attract talented women and to create role models. We were fortunate to win Dr. Fine Fiedler as the deputy coordinator. Every effort will be made to continue these promising trends. Most helpful mechanisms are the tenure track or multi-track programs of the Helmholtz centres and the instrument of Helmholtz Young Investigator groups.

3.2.1 Sensors, ASICs and Interconnects

The work in this subtopic is focused on the development of state-of-the-art as well as emerging hardware technologies involved in building particle and radiation detectors for future scientific experiments. Most of these technologies are generic and can be applied to different kinds of detectors used in different experiments including photon science, high-energy physics (HEP), nuclear and hadronic physics, astroparticle physics and neutron scattering. This creates not only synergies between the various research centres but also cross-fertilisation between the different research fields. It should be stressed that although these technologies are state-of-the-art, they are by no means "blue-sky". All developments are carried out with clear ideas of how they will be used in real applications and experiments.

Currently, the activities in this subtopic include: solid state hybrid-pixel detectors, which have revolutionised HEP and photon-science experiments and are now entering the consumer and medical imaging markets; gas-based systems, which are essential in nuclear- and high-energy physics experiments, ultra-fast detectors for sub-nanosecond timing, and finally monolithic CMOS imagers which are rapidly evolving.

A close link exists with subtopic two, which is investigating high-speed data transmission, needed to handle the enormous data rates generated by the new generation of detectors. Furthermore, there are links to subtopic three, where complete systems are assembled and tested. This provides important feedback for the technology developments.

3.2.1.1 Challenges

The construction of new colliders and photon sources, scheduled upgrades of existing colliders and continual improvement in brilliance of synchrotron storage rings pose formidable challenges for the detectors, especially the front-end parts. These new and upgraded machines will provide orders of magnitude more signals to detect, process and record. This goes hand-in-hand with drastic increases in radiation doses and dose rates. At the same time, the total amount of material used to construct the detectors has to be greatly reduced, so that advances in granularity ultimately translate to an improvement in resolution. Wherever possible the developments undertaken to meet these challenges should be as widely applicable as possible so as to profit from synergetic effects and to facilitate spin-off into society, for instance in the field of medical and non-destructive X-ray imaging.

Sensors

A first step in particle detection is the transfer of energy from the particle to the sensor. Depending on the application different mechanisms and processes are involved, including ionization, scintillation, excitation of phonons and breaking of Cooper-pairs. In this programme the main focus is on solid-state semiconductors and gas-based systems. The grand challenge is to develop the technology required to build particle detectors for future accelerators and sources which will provide the performance needed to do the science intended and which will have lifetimes commensurate with the operation of the sources and experiments. Tracking detectors at future accelerators, especially in the regions close to the interaction region or the beam, will have to survive in extremely challenging radiation environments while still enabling precise particle reconstruction. Similar challenges are present in nuclear reactors, synchrotron and FEL sources as well as in medical imaging. Therefore, a deeper understanding of radiation damage and development of sensors that are radiation-hard is of great importance. For tracking devices at the high-luminosity LHC, bulk damage of the silicon sensing material from non-ionising energy loss is the dominant effect that deteriorates device performance. Surface and interface damage caused by ionising radiation has to be considered for sensors placed close to the beam at hadron- and at e+e- colliders, as well as at synchrotron and FEL sources. Various types of silicon (different growth conditions) and special radiation-hard designs are available, and need to be studied and understood at a fundamental level. In addition, alternative materials, like diamond, are potential candidates that will be investigated. Diamond will also need to be further studied for applications of in-beam detection with high ion rates at FAIR.

Besides radiation hardness, optimal coverage is another important aspect. Multi-megapixel X-ray imagers are constructed with modules tiled together in the focal plane. With the current state-of-the-art technology there are relatively large insensitive areas at the edges of the modules, due to the wire-bonding of the readout chip and the extended guard ring structures of the sensors. This results in a reduced fill factor in the focal plane and subsequent loss of important information. The challenge is to construct multi-megapixel imagers with a 100% fill-factor by using advanced sensor processing technologies, combined with post-processing of the readout chips to create through-silicon-vias for backside contacting.

A further requirement is the optimization of the sensor quantum efficiency. An increasing number of scientific applications at the new photon sources demand the use of photon energies above 15 keV, where silicon sensors rapidly become inefficient. Novel high-Z semiconductor materials are being developed throughout the world, not the least driven by requirements in medical imaging applications. Cd(Zn)Te, GaAs and Ge are the main candidates, depending on the photon energy range. The challenges lie in obtaining high-quality material, in subsequently processing the material into pixelated sensors and in hybridisation with readout ASICs. For applications where the highest spatial and energy resolutions are not required, fast scintillators, directly coupled to the silicon sensor, are an attractive alternative. For this, both the suitable scintillators and deposition techniques need to be developed.

Detectors based on gaseous media remain excellent candidates to meet the requirements of fast tracking and high energy resolution with low material budget in high-energy and particle physics experiments. Despite their long-term use in all kinds of gaseous detector-systems in many physics experiments, basic knowledge on the properties of gas compounds is still not complete. Consequently, even state-of-the-art simulations often fail to reproduce their behaviour. As an example, the simulated response to highly ionizing particles and the predicted gain in amplifying arrangements such as Gaseous Electron Multipliers (GEM) or Micro-Mesh (MM) are often still inconsistent with experimental findings. In order to cope with the increasing luminosities of future facilities, a change to specially “designed” multi-component gas mixtures, other than the well-established “standard” noble gas and quencher combinations such as Ar/CO_2, is required. Understanding of the interplay of these components relies on the knowledge of basic data. In addition we need to understand the effects of outgassing as well as radiation induced aging of novel materials used in the construction of gaseous detectors. This is an essential ingredient for the construction of robust detector solutions.

Readout Electronics

Once a particle of interest has deposited a fraction of its energy in the sensor, this (weak) signal needs to be amplified, processed, buffered and sent out of the detector by the readout electronics. The requirements for readout electronics at upcoming collider experiments, like HL-LHC, CLIC and ILC, heavy-ion and hadron facilities like FAIR and especially at X-ray Free Electron Lasers are challenging for planar CMOS ASIC technology. The characteristics of the new accelerators and sources lead to an increased occupancy, which in turn requires a much higher detector granularity and thus a higher density of readout channels as well as much faster signal processing inside the readout electronics. In addition, the large experiments at FAIR as well as the developments for gamma and neutron detectors plan to use self-triggered front-ends with online event reconstruction and selection instead of a global trigger system.

Moore's law has provided CMOS technology with ever-increasing circuit density. This allowed for more functionality and higher granularity, with improved radiation tolerance as a fortuitous side effect. As a result 0.25 micron CMOS technology could be employed for large scale instrumentation of the LHC experiments with silicon detectors. Further reduction of the feature size will, however, give a diminishing return. CMOS processes of very small feature size (i.e. <45nm) are much less attractive for analogue detector readout amplifiers. In addition, the dynamic range is greatly reduced due to limited supply voltages (only 0.8 V for 45 nm, versus 2.5 V for 0.25 microns), whereas high dynamic ranges are required for many experiments at FAIR and the European XFEL. As a remedy, novel circuit concepts, like dynamic gain switching, ADCs included into the preamplifier and current signalling techniques, have to be developed and evaluated. To address the challenges in front-end synchronisation and data transport for triggerless systems of very high channel density such as the FAIR tracker systems of CBM and PANDA as well as the HL-LHC detector upgrades, new readout architectures have to be developed and high-speed serial links have to be integrated on or at least very close to the front-end ASIC, as there is no physical space available for any broad data busses. These novel circuit concepts require more real estate, which clearly conflicts with increased granularity or shrinking pixel sizes in pixel detectors, even when using 65nm CMOS nodes. Mainstream commercial CMOS components, like DRAMs or System-On-Chips (SOCs) for smartphones face the same problem. DRAM manufacturers and cutting-edge foundries embarked on using the third dimension by stacking CMOS circuits by what is called 3D-integration. A main goal during this PoF period is to get access to and develop further 3D-integration of ASICs for pixel detectors. The potential advantages this technology provides are:

- Increased functionality, for instance the second tier can immediately be used to increase the number of frames that can be stored during a bunch-train at the European XFEL, allowing full use of the available luminosity.
- Communication between detector channels or pixels, together with local intelligence, can be implemented in an additional tier and employed for real-time data processing or data reduction already on the front-end level. This will reduce the demand in bandwidth for detector readout, data processing and storage.
- Through-silicon vias (TSVs) enable the integration of readout circuitry like readout buffers, multiplexers or serialisers on the bottommost tier, eliminating the dead area occupied by these circuits and by the wire-bonded interconnections in planar technology. This will allow the construction of "edgeless" detector tiles.
- The current developments focus on intelligent digitisation with large dynamic range working in a triggerless environment. 3D-integration for these applications would be an option to integrate detector specific front ends onto a generalised digitiser ASIC.

Another challenge, imposed by CVD-diamond detector technology aiming at picosecond resolution time measurements of minimum ionizing particles, is the design of ultra-fast ASICs with bandwidths from 1 MHz to 6 GHz, which at the same time provide single-particle sensitivity and high-rate capability at 100% detection efficiency.

Besides the technical challenges listed above, there are also very important infrastructure aspects within and between the Helmholtz centres. Due to the high cost involved in producing multi-tier chips, reliable methodologies for pre-silicon verification by simulation have to become an essential part in chip design, and the corresponding methods and tools needed for simulation and verification of a CMOS design need to be adapted to the new technologies of 3D-integration. Another major challenge is to create and foster common shared libraries of designs and building blocks as an infrastructure throughout the participating Helmholtz centres. A large step in this direction has been made in the context of the Helmholtz Detector Technologies and Systems Platform during the previous PoF period, where 65nm TSMC (Taiwan Semiconductor Manufacturing Company) was chosen as the common next node and a design repository was set-up.

Last but not least, another important requirement is to increase the know-how and competence in the field of designing Monolithic Active Pixel Sensors (MAPS), also known as CMOS sensors. This is considered to be strategically important for various reasons. In-depth understanding of the possibilities and limitations is crucial for a most fruitful collaboration with CMOS designers outside the Helmholtz centres. Furthermore, back-thinned and back-illuminated CMOS sensors are considered as the most promising technology for soft X-ray imaging, and various systems are expected to be built during the PoF-III funding period. Back-thinned CMOS systems are also increasingly employed in detectors for both particle and nuclear physics. MAPS detectors have successfully demonstrated their potential. They are now even a baseline choice for the next set of vertexing detectors for heavy ion physics, which are currently being built (FAIR CBM, ALICE ITS upgrade). The Helmholtz internal CMOS design capabilities will be complementary to other groups and should lead to even closer collaborations with, for instance, the groups of M. Winter at IPHC in Strasbourg and R. Turchetta at STFC/RAL. Other promising particle detection concepts to be watched are high-voltage CMOS processes with integrated amplification stages.

Interconnects, Packaging and Innovative Materials

Building particle detectors has always created a challenge for electronic packaging and interconnect technologies. With the future colliders and sources, like the HL-LHC, the ILC and the European XFEL, these challenges will be even higher. For instance the required spatial resolution and focal-plane fill-factors will put extreme demands on the packaging technologies. At the same time the amount of material has to be further decreased, while the heat loads of front-end electronics will go up with channel count.

Many industrial solutions are intended for series production, and thus are developed on wafer level. Process examples are under-bump metallisation (UBM) and micro-bumping which are commercially available for hybridising 3D modules. However, these processes are not suitable for rapid prototyping and small-volume production. Hence, packaging techniques for a small number of demonstrators need developing. The installation of a lasting, flexible, and reliable supply chain for packaging of 3D module prototypes is a very demanding task and comprises high-density vertical (or 2.5-D) packaging technologies as an intermediate and complementary process. At the same time, upscaling of these processes to small-volume production is required. This will allow profiting from the flexibility at affordable costs. Besides providing rapid prototyping and small scale production capabilities, various production techniques envisaged in industrial roadmaps until 2020 must be adapted for detectors. Among these are serial techniques in micro-solder bumping with diameters down to 10 µm or less, bump-less or copper-pillar bumped tiles, pre-coated powder sheets and flip-chip (FC) bonding techniques capable of handling large dies of ~50 µm thickness and achieving a post-alignment accuracy of 2 µm. The increasing demand in interconnection density, power distribution, and migration of functionalities into a single package requires advanced interposer technologies. These technologies utilise advanced or novel materials, with redistribution layers in thin-film technology

(TFT), through-substrate via formation techniques and IC-layer stacking solutions. Corresponding new packaging architectures enable a “More-than-Moore” equivalent scaling through functional diversification and heterogeneous integration. For example, the on-going downscaling towards ultra-deep submicron CMOS technologies will drastically increase the inter-chip data-throughput requirements calling for the integration of electro-optical and optical devices. It is important to point out that packaging is a very active and important field in the consumer electronics industry, but these technologies need significant modification or adaptation to be applicable to building detectors. Such an adaptation can only be done by the research centres themselves. Finally, having the capabilities for advanced packaging inside the Helmholtz structure will give a significant cost reduction, for prototyping as well as for detector scale series production.

Packaging presents a multi-facetted challenge including the extraordinary alignment and processing requirements of multiple dies on large-scale substrates, mixed interconnects including wire-bonding from top and bottom sides, flip-chip bonding, dispensing, gluing, curing and metrology. Furthermore, automated assembly processes have to cope with the delicate mechanical constraints of novel materials and packaging architectures. In order to meet this challenge the entire spectrum of packaging techniques needs to be addressed.

Multi-physical aspects like electrical, thermal and mechanical behaviour as well as the influence of exposure to irradiation are important topics in the assembly of detectors, especially in the case of heterogeneous chip-to-chip or chip-package interconnects. The coefficient of thermal expansion (CTE) mismatch affects the reliability of bump-bonds and through-substrate vias, as well as the integrity of dielectric films and large subassemblies. Hence quality control is a mandatory task in order to reach production yields above 90 %. Design-for-testability and built-in testing as well as optical and X-ray inspection techniques are essential and dictate future requirements since the access to electrical contacts of embedded ICs in complex packages is limited.

The LHC experiments are planning major upgrades of their detection systems in preparation for the LHC upgrade which will increase the instantaneous luminosity by a factor of 5 (HL-LHC). The expected running conditions at the HL-LHC imply operating the detectors at -20°C, which sets high demands on the choice of materials, and the overall amount of material must be reduced in order to improve track and momentum reconstruction precision. Low-temperature operation inevitably results in mechanical stress due to differences in CTE, which can reduce the lifetime of the active sensor material and has to be minimized. Moreover, once installed and in operation, tracking detectors are typically inaccessible for repair and thus special attention has to be drawn to the longevity of all components. Here the longevity of adhesive joints after several thermal cycles and radiation tolerance in general are of particular importance. These requirements can be met by utilising novel materials.

At the ILC the reduction of material of the tracking detection system is of even higher importance. The challenge in the design of these ultra-lightweight detectors is to keep the material budget per detection layer below 0.35% of a radiation length.

For gaseous detectors, it is of utmost importance to develop innovative structural materials and components such as light-weight field cages, stable ceramic-based readout structures, and detector housings. These materials need to have low-atomic numbers and minimum absorption, with optimised material budget and radiation hardness while having at the same time suitable electrical and thermal performance.

A large fraction of the current material budget of detector systems in high-energy physics experiments is taken up by insensitive material like services and infrastructure (support, cables, cooling, electronics, and beam pipe). Reducing this contribution is the main challenge in future designs. It can be met by new concepts of using multi-purpose materials and interconnects where all the composing parts are stripped to their major functional tasks. With conventional materials, the reduction of material contradicts the goal of efficient cooling, when relying on thermal conduction from the heat source to the heat drain. In order to solve this contradiction, innovative cooling schemes need to be investigated and developed. Various promising concepts exist and are being studied, like micro-fabricated cooling channels located at the heat source, CO_2 cooling, and specifically the combination of the two.

3.2.1.2 Current Activities and Previous work

During recent years DESY has developed various hybrid-pixel X-ray detectors, one of them being the LAMBDA (Large Area Medipix-Based Detector Array) system. This system was subsequently taken as the basis for a common development platform by the partners of the Helmholtz Detector Technology and Systems Platform. This development platform, termed Helmholtz-Cube is depicted in Figure 23. The approach has the great advantage that a newly developed component can readily be tested by integrating it into the existing system. As an example, within the Detector Technology and Systems Platform, high-Z sensors were developed and hybridised to the existing readout chip, and could be immediately tested by using all other components of the Helmholtz-Cube. This allowed developers to fully concentrate on their core-activities, without the need to re-develop the entire readout chain. This Helmholtz-Cube serves not only as a development platform in subtopic one, but will also be used for the high-speed IO developments in subtopic two and was also spun-out as a prototype system for photon-science experiments in subtopic three. The experience gained in using the system in real experiments is subsequently fed back into the developments.

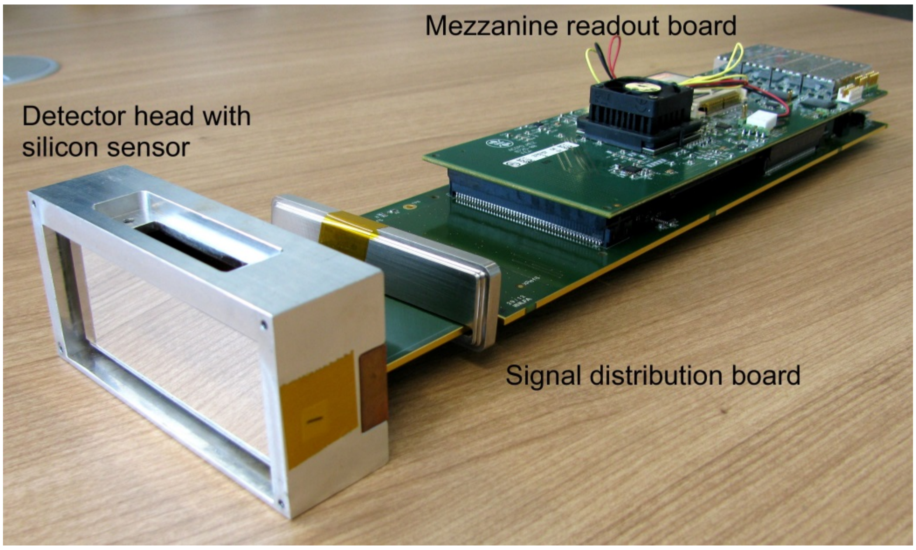

Figure 23: Picture of the Helmholtz cube.

Sensors

Within the participating Helmholtz centres, and in collaboration with various university groups, there is a large and increasing expertise in the field of sensor development and characterisation, including radiation-hard, slim-edge, high-Z, and diamond sensors. In recent years, various types of sensor materials and designs appeared on the market with the potential of being more radiation-hard, for example planar epitaxial silicon, magnetic Czochralski (MCz)-silicon, diamond, 3D silicon sensors or high-voltage CMOS sensors. Both KIT and DESY are currently involved in investigating radiation damage in sensor materials such as various flavours of silicon and diamond. In the framework of the RD50, ATLAS and CMS collaborations, the groups take major roles in the development of planar silicon sensors through device layout and characterisations, complemented by T-CAD simulations. KIT provides support to external groups concerning sample irradiations at the Karlsruhe cyclotron and both groups also use the CERN PS facility and the Ljubljana reactor. Measurements of sensor efficiencies, Lorentz angle and readout chip parameters before and after irradiations are performed. For the study of radiation hardness of diamond detectors, Helmholtz centres play a significant role in the RD42 collaboration. In the framework of the European XFEL DESY and the University of Hamburg have studied the X-ray induced radiation damage in silicon sensors up to doses of 1 GGy. This has resulted in a worldwide unique understanding of the processes involved and facilitated a special radiation-hard sensor design for the AGIPD detector for the European XFEL.

The R&D on diamond detectors at GSI, DESY and KIT has been focused on the characterisation of advanced ‘detector-grade’ CVD-diamond materials and feasibility studies to build systems for specific heavy-ion and MIP detection. In addition, GSI and DESY have been testing the novel, highly promising Diamond-on-Iridium (DOI) material produced by CVD onto four inch iridium substrates at the University of Augsburg. For the various applications at GSI both fast timing and spectroscopy diamond assemblies were needed. KIT is responsible for the Beam Condition Luminosity (BCM1L) sensors of CMS, whereas DESY Zeuthen is deeply involved in the preparation, test and operation of the fast component (BCM1F) of the CMS BCM system. These devices are mounted in locations where radiation exposure of the sensor is particularly high (high neutron background). KIT successfully developed a new model to describe radiation damage in semiconductors based on the Displacements Per Atom (DPA) parameter.

DESY and KIT, as part of the Medipix-3 collaboration, have been part of a large first study of production and processing of slim-edge and active edge sensors, using different silicon materials (p-on-n, n-on-p, n-on-n) and thicknesses. The resulting systems are currently being tested and compared between various international partners. First results show the clear possibility of producing and processing slim-edge silicon sensors.

In the last decades several room temperature high-Z semiconductor materials have been investigated but only two candidates showed promising results. These materials are Cd(Zn)Te and GaAs. Both CdTe and CdZnTe show an excellent performance for X-rays from 40 keV up to 200 keV energies. GaAs is suitable for the energy range from 10 keV up to 80 keV. The Freiburger Materialforschungszentrum (FMF), KIT and DESY have a long-term experience in the development of X-ray detectors using high-Z materials like GaAs, CdTe and Ge. The groups at the FMF and KIT have developed different methods of material characterisation, detector processing and testing of high-resistivity semiconductors. DESY, FMF and KIT are members of the Medipix 3 collaboration and have access to sophisticated readout electronic chips. The FMF has developed a low temperature flip-chip bonding technology optimized for high-Z materials and the fine pitches of 110 and 55 µm. Monolithic sensors of both GaAs and CdTe with ~ 400k pixels have been hybridised successfully to 6 Medipix-3 readout chips and have been integrated into the Helmholtz-cube. X-ray images have been obtained, proving the excellent performance of the systems, with over 1000 frames-per-second and spectroscopic imaging capabilities. Recently, DESY and Canberra have successfully developed Ge pixel sensors with 55 µm pixel pitch, which again were hybridised to Medipix 3 readout chips. Ge has the same stopping power as GaAs, but has the advantage that it is available in large sizes and near perfect quality. The fact that Ge needs cooling, due to its small band gap, is an acceptable inconvenience in many scientific applications.

In order to meet the requirements for ultra-fast timing applications for radiation tolerant gaseous detector systems, specialized ceramic materials have been developed in cooperation with partners from Fraunhofer institutes. Used as electrodes in multi-gap resistive-plate counters (RPC) very good time resolution (~50ps) and high rate capability, up to 500 kHz count rate at 90% efficiency have been shown. Further improvements need a thorough and detailed understanding of gas multiplication processes to be studied with fs-lasers.

Readout Electronics

Both DESY and GSI have many years of experience in designing state-of-the-art readout ASICs for scientific applications. DESY developed readout ASICs for a 7-element silicon drift detector at the DORIS synchrotron, combining high-speed and medium to high energy resolution. These systems have been in routine use for many years at various experimental stations at DESY. One of the senior ASIC designers has been responsible for essential parts of the well-known and widely used BEETLE readout chip. DESY has also been involved for many years in developing (two-tier) 3D integrated read chips. Over the last years DESY, in collaboration with PSI in Switzerland, has developed the Adaptive Gain Integrating Pixel Detector for the European XFEL featuring low-noise and large-dynamic range as well as 5 MHz framing possibility. DESY is also responsible for significant parts of the ASIC development for the DEPMOS Sensor with Signal Compression system optimised for the soft X-ray range, also developed for the European XFEL.

GSI has developed specific front-end ASICs for diamond detectors and fast photon detectors. As diamond detectors are very promising as start and beam monitoring detectors in high-luminosity experiments, precise time digitisation combined with high-rate capability is a major issue. There is considerable experience at GSI in this field and suitable time-to-digital converter cores have been developed during the last years. In parallel there is an on-going evaluation of self-triggered transient recorders with large dynamic range for spectroscopic use. Transient recording enables the use of pulse shape analysing algorithms for pile-up detection and particle identification through e.g. electromagnetic and hadronic shower discrimination. Additionally, GSI has thorough experience with the employment and the corresponding architectural needs of self-triggered front-end ASICs in prototype detectors towards the free streaming detector applications at FAIR.

Furthermore, FZJ started activities on transferring the existing know-how on advanced pixel-detector front-ends into advanced readout chips for combined usage as straw-tube readout for PANDA and in new types of neutron-detectors like Wavelength Shifting Fibres.

A 65 nm CMOS process has been selected as the common next node throughout the participating Helmholtz centres. The corresponding design kit has been installed at the different sites and is evaluated for its suitability for future developments of ASICs. The implementation of a design repository is on-going; it will either be based on a commercial solution that seamlessly integrates into commonly used ASIC development tools or a more standard stand-alone repository with revision control system. The repository is considered a prerequisite for simultaneous work on the same design in different Helmholtz centres. A similar approach has been successfully used for the development of the AGIPD readout ASIC. By providing proven circuits and offering ready-to-use building blocks, such a repository also substantially lowers the barrier for smaller groups at Helmholtz centres or universities to get involved in ASIC design activities. This repository will not be limited to one single CMOS technology, but will be open to include others in the future as well.

Various Helmholtz centres have used and integrated CMOS sensors developed elsewhere into experiments and test beam setups over the years. This required close interaction between the centres and the outside designers, in order to define ambitious but realistic targets, and to ensure a smooth implementation and deployment in the experiments. DESY has recently started a large project to design a high-speed large area CMOS imager for the soft X-ray applications at FELs and storage rings. This development (Percival) is carried out in close collaboration with STFC/RAL for the design and fabrication.

3D-integration of ASICs relies on three key technologies, which have reached different levels of maturity. The first technology is back-thinning, i.e. the removal of a large fraction of the bulk silicon material to facilitate the processing of through-silicon vias (TSVs). Since the technology is also used in standard wafer processing, it is widely available. The second step is the production of TSVs to electrically connect the circuit tiers through the bulk silicon material to the outside. This technology is available from several vendors, differing in interconnect size and maximum thickness of the bulk material. The most challenging part of the process is currently wafer bonding. The circuitry-loaded surfaces of two wafers are bonded together face to face, forming a sandwich with two tiers of CMOS circuitry on the inside. The expectation is that the turn-around time for production will drastically shorten over the coming 3 to 5 years, making this technology a viable option for developing and building innovative particle detectors. DESY being a member of the Medipix-3 collaboration has been involved in the development of TSV technologies for back-side contacting (CEA-LETI, France). Also, a two-tier ASIC based on the AGIPD circuitry has been designed and submitted, and delivery is expected shortly.

Interconnect, Packaging and Innovative Materials

A main mission of the Helmholtz centres is to provide working detector systems and to integrate them into the experiments. Therefore electronic packaging activities have always been a core part of detector instrumentation at the centres. One focus is on high-density interconnect technologies for hybrid-pixel detectors. KIT and DESY have installed machinery and are establishing the flip-chip bonding production processes required for the CMS detector and other applications. Furthermore, new balling technologies like jetting and stud-bumping, with solder ball diameters down to 40 µm, have been tested. These technologies allow low-cost balling processes for small series, while having the potential to be scaled up for a large-area detector. In addition to the flip-chip processes, wire-bonding technologies have been improved by the acquisition of automatic high-speed ball-wedge gold bonders. These capabilities allow for the complete assembly of prototype systems in-house, and thus greatly reduce the development turn-around times. In the field of substrates new technologies were demonstrated to directly print thick film structures with a pitch of 100 µm on Al_2O_3 substrates. Also, low-temperature co-fired ceramics (LTCC) material is used to combine mechanical, electrical and even thermal functionalities in a single substrate. The LTCC substrates are widely explored and used for the detectors for the European XFEL.

These advancements of the packaging and interconnect technologies require sophisticated quality management and control techniques. Therefore, generic electrical test stations are being developed to test the assembled sensors and the readout electronics. Additionally the material characterisation methods have been improved by extending the metallographic sample preparation feasibilities.

Novel detector modules are being designed at DESY guided by extensive thermal and mechanical finite element analyses (FEA). This new approach, which is generally applicable, is mainly driven by the upgrades of the tracking detectors of both the ATLAS and CMS experiments, which are in a very early research and development stage. For CMS, for instance, these new modules will consist of a sandwich of two silicon strip sensors at close distance, which, in conjunction with the strong magnetic field of CMS, will allow for a momentum measurement on the module. Similar mechanical FEAs were carried out for large support structures for Time Projection Chamber (TPC) field cages in the framework of the ILC detector research and development. Even though this work is closely steered by specific high-energy physics experiments, the approach and acquired know-how is of general interest and use. An excellent example of a detector with minimal material is the PLUME module given in Figure 24.

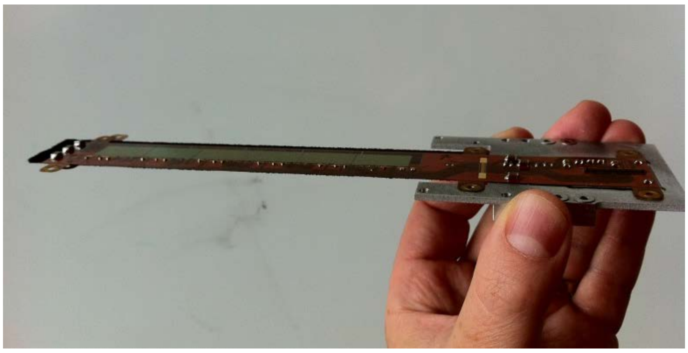

Figure 24: Picture of a prototype Silicon ladder developed within the PLUME project.

The insight obtained by finite element analyses has to be complemented by destructive and non-destructive measurements. For this purpose, the procurement and commissioning of the necessary laboratory infrastructure has started. These laboratory setups will allow the thermal and mechanical characterisation of test structures, prototypes and final detector components.

The first lightweight and stable ceramics electrodes as well as lightweight detector housings for gaseous detectors have been built and tested in the past. Furthermore, an ultra-lightweight and highly structured field cage system has been designed and characterised. Investigations in novel materials for field defining structures have started and a test system for the determination of volume-resistivity of large area samples has been set-up and operated. To complement this work, a gaseous-detector ageing test stand was built and commissioned. Through high gain stability, it allows studying ageing of selected materials in a short time. A test stand employing laser-driven gas ionisation capable of signal generation in small volumes (few μm^3) allows for the measurement of drift velocity and Townsend-coefficient at the same time and under the same conditions.

In addition, prototype silicon substrates with micro-fabricated cooling loops have been produced and are under test in order to gain experience with this novel cooling concept in terms of assembly and handling.

3.2.1.3 Objectives

Sensors

Detectors and sensors close to beams and interaction points will experience doses which largely surpass what the current best sensors are able to withstand, new developments are required. In order to be able to make the right choice for the sensor materials and structures for HEP, nuclear, hadronic and X-ray experiments at future accelerators and colliders, the different processes involved in bulk and surface radiation damage need to be understood better. The aim is to collect a comprehensive set of information about the properties of the studied sensors with respect to their radiation hardness. In order to achieve this, irradiation campaigns will be conducted on different sensors using the proton cyclotron at KIT (25 MeV protons), the reactor in Ljubljana (neutrons) and the test beam infrastructure at DESY. Materials such as magnetic Czochralski and epitaxial silicon offer different properties compared to “standard” float-zone silicon such as higher oxygen content or high purity. Structuring the devices as planar p-in-n or as n-in-p sensors with different strip isolation techniques or considering 3D sensors and high-voltage CMOS sensors will have a major impact on the radiation hardness as well. The radiation effects result from both surface and bulk damage and it is important to investigate the interplay of both. The irradiations will be followed by detailed characterisations of the induced radiation damage and finally coupled to simulations using sensor design (TCAD) software.

The same radiation-hardness test protocols shall be applied to detector-grade CVD-diamond materials, with specific attention to the radiation resistance of the detector contacts and the diamond surface-metal interface. The main objective concerning diamond sensor materials is the production of several-square-centimetre detector-grade samples. This will be done by exploring new growth and post-processing strategies for the efficient reduction of structural bulk and surface defects, which at present limit the high potential of this material. Comprehensive characterisation and comparison of the electronic properties of single-crystalline, poly-crystalline, and Diamond-on-Iridium (DOI) sensors will complete the schedule. Eventually, the recently invented technologies for diamond membrane detectors as well as of 3D and silicon-on-Diamond (SOD) devices shall be developed, aiming at improved heavy-ion and MIP detectors, respectively.

For the mega-pixel X-ray imagers, the performance of slim-edge silicon sensors from various suppliers, including VTT, Sintef and FBK, using different types of sensors (p-on-n, n-on-n and n-on-p) and different edge treatments (slim-edge, active-edge etc.) will be investigated. Based on the results of this research the most appropriate supplier and technology will be selected. In conjunction with subtopic three, a large-area imager with close to 100% fill-factor will be constructed. This development will have to go hand-in-hand with the development of through-silicon vias, required to contact the readout ASICs from the back-side, thereby avoiding the need for wire-bonding and its associated large dead area. This development forms part of the packaging activities described below. The technology will subsequently be applied to the AGIPD detector system, to create a next generation detector for the European XFEL.

For the development of X-ray imagers for energies above 15 keV the processing capabilities for CdTe and GaAs sensors will be further developed and, in close collaboration with the packaging experts, the hybridisation process further optimized. After the successful production of cameras with a few 100 kpixels, the goal is to be able to build a mega-pixel camera, with a good homogeneity and a yield better than 98 percent. For this, the existing interconnect technology has to be modified to guarantee homogeneous processing and handling of multi-chip units. Also, tools have to be developed to achieve a positioning accuracy better than ±5 µm. All technologies have to be compatible with the processing of high-Z materials which requires low temperature (<120 ^{o}C) and low force. Similar to the silicon sensors, slim-edge high-Z sensors will be required to reach an acceptable fill factor. The development of slim-edge technology includes the following tasks: sophisticated dicing by a diamond blade saw; polishing and lapping of the cut edge; etching and passivation of the cut edge; adjustment of the layout for guard-ring and pixel contacts. The final goal for the GaAs and CdTe pixel detectors is to have an inactive width from the edge of the sensor to the first pixel row of only 50 µm.

In addition to CdTe and GaAs we will continue the development of Ge based pixel detectors. Now that the technologies for sensor fabrication and processing have been proven and established, large-area sensors needed to construct multi-mega pixel systems will be developed.

In order to improve the understanding of fundamental processes involved in the operation of gaseous detectors, the knowledge base will be extended with precision measurements of at least the main components of widely used gas-mixtures under various conditions in terms of e.g. ion mobility, diffusion, recombination, attachment, e^- cross sections and photon interactions.

To determine effects of radiation (aging) of innovative materials used in the construction of gas based systems, a dedicated set up for the enforced radiation aging will be operated and refined to support the engineering activities towards robust gaseous detectors.

At high particle rates the build-up of space charge in the gas volume by slowly drifting ions leads to distinct distortions of the electric field, spoiling timing and spatial resolution properties. To overcome this problem, the Ion Back Flow (IBF), amongst other phenomena, will be investigated and reduced e.g. by applying well-known gating techniques using electrode arrangements with relatively large geometrical aperture (<20%) and optimized transparency (>50%). A detailed position-resolved study of the avalanche build-up and of the charge collection properties will be performed in order to gain deeper insight in the main processes of amplification. This will also be used to model different detector designs. In order to simulate ionization signals over a large dynamic range of impinging particles, from MIPs to Highly Ionizing Particles (HIPs) dominant e.g. at FAIR, optical (laser) and radiative methods will be applied.

Readout Electronics

In order to meet the unprecedented requirements imposed by the new accelerators and colliders, novel readout architectures will be investigated, designed and implemented in 2D ASICs using the advanced 65 nm TSMC technology. This includes pixel-to-pixel communication schemes, as well as high-speed and large dynamic range digitisation in the pixel with the aim of broad re-use in other detector applications. These designs will then be used to produce the next generation readout chips for instance for the European XFEL. They will also be used for developing a common two-layer (“two-tier”) read-out ASIC. As explained in the “challenges” section the use of the third dimension is driven by the requirements from various experiments. One goal during the PoF-III period is to produce a 3D-integrated mixed-signal readout ASIC, manufactured in a deep sub-micron CMOS technology, and suitable for integration in the Helmholtz-Cube. The design specifications are a combination of photon-science and HEP requirements, and push the limits of pixel size, noise, frame rate, dynamic range, radiation hardness and tileability.

The target system envisioned consists firstly of an analogue tier that will be bump-bonded to a sensor, which will amplify and digitise the charge and store it locally. This analogue tier will be coupled to a digital tier, which will perform local data processing on the stored images in photon science. Track reconstruction, hit finding or local trigger processing are possible tasks performed by the digital tier in high energy physics, heavy ions, neutron scattering and related fields of application. Until the required 3D-interconnect processes become available, the development of the chip architecture can be performed by arranging the analogue and digital parts in a checkerboard pattern, called a 'tier-tile' layout, and connecting these parts via the top metal layer. At the expense of the pixel size, this approach permits the evaluation of functionality and architecture before the wafer bonding process becomes available.

In the field of readout for diamond detectors a dedicated readout ASIC is required which differs significantly from the above described system. As diamond detectors show an excellent time resolution and radiation tolerance, the primary application of these detectors is their use as start- and beam monitoring detectors. Here the weak response of diamond detectors to ionizing radiation puts special demands on the frontend electronics. On the other hand, the number of channels is modest. For this application a readout ASIC will be developed which integrates the high-speed front end and the high precision time to digital converter core. The integrated data acquisition and transport will be able to cope with a rate of several MHz per channel.

Because a low-inductance connection is mandatory for the fast detector signals, it is planned to connect the System-on-Chip (SoC) with flip-chip technology to the carrier board. Direct connection to the detector is also an option.

During the PoF-III funding period the goal is to develop a number of systems for low-energy X-ray detection, based on the ongoing Percival system, but having specific performance characteristics like high frame rates, or small pixel sizes. This will be partly done in collaboration with outside groups and partly by developing in-house design capabilities. For the next generation of particle physics detectors at both the LHC and the ILC, MAPS with advanced capabilities need to be developed with the goal to further enhance the speed, reduce the material and increase the radiation hardness beyond the performance of the current generation of MAPS devices. These devices will then be key building blocks for these future detectors. All these developments take place in international R&D groups, where the designers of the Helmholtz centres are very actively participating. A strong synergy for technology development, including circuit design principles and post-processing steps, will be created between the Photon-Science and HEP communities. The final systems will be specific and tailor-made for each of the applications.

The Helmholtz centres involved in ASIC design will continue to strengthen their links and interactions. One of the main vehicles towards this goal is the use of a common node (65 nm) and foundry (TSMC), as well as the creation and build-up of a design repository at DESY. This repository will be available for all Helmholtz centres as well as participating universities. In addition, joint ASIC design workshops will be organised annually.

Interconnects, Packaging and Innovative Materials

Currently the production technologies for hybrid semiconductor detector modules are mostly semi-automatic. It is planned to further automate the involved processes with the goal to improve the yield and to reduce costs. Modules and staves with solder balls down to a size of 10 µm will be automatically assembled. A key technology to reduce the costs is the balling technology, which will be established for 40 µm balls by solder jetting and will be done in-house. Another promising technology for the balling process will be PPT-technology (Pre-coated Powder Sheet) which might allow the cost-effective balling of sensors and ROCs with a pitch of down to 20 µm. 3D-chipstacks with TSV interposers will be used to qualify the new production technologies. Both balling technologies will be evaluated and adapted to the production of complete detectors.

As high yield is mandatory for a cost-effective and predictable production of units, the quality of the processes need to be ensured for every production step. Special X-ray inspection and electron microscope techniques, with a resolution better than 1 µm, will be established to guarantee the production quality

In addition to the sensor packaging, the standard electronic integration will be continuously improved, enabling finer pitches on organic and ceramic circuit boards and addressing the new thermal challenges due to higher switching speeds of the chips.

In the upcoming PoF-III period the investigation of novel structural materials and electronics substrates with respect to their usability on high-energy physics as well as X-ray imagers will be widened. The existing experience in the field of finite element analyses that have had a great impact on detector development will be solidified and extended. In particular, micro-fabricated cooling supplies will be designed and optimised by utilising computational fluid dynamics analyses. Moreover, it is planned to simulate the mechanical and electrical properties of fibre and matrix compounds for gaseous detectors.

The simulation and modelling activities will be complemented by the characterisation of test structures and prototypes in the infrastructures available within the participating Helmholtz centres. Fibre and matrix composites as well as carbon-loaded electrically conductive materials will be investigated with respect to their usability as field defining structure in gaseous detectors that can replace the typically used copper and further reduce the amount of material employed. For this purpose, new structuring techniques for these field-defining structures - both 2D and 3D - will be developed.

Doping of materials such as fibre reinforced composites and glues offers a promising solution for enhancing certain material properties. Here composites and glues loaded with nano-particles are of particular interest as they make it possible to engineer materials for a specific task and application. It is planned to design, fabricate and characterise such compound structures for the use in both semiconductor tracking and gaseous detectors for high energy physics experiments.

Further research in the direction of micro-fabricated cooling devices will be carried out. For the development of the next generation of X-ray imagers, it is planned to develop a rigid electronics substrate with integrated cooling channels that will allow the cooling of the front-end electronics with maximum efficiency. For high-energy physics tracking detectors the employment of silicon micro-channel cooling devices will be explored by cooling prototype detector modules.

In the beginning of the next funding period, the research and development of the detector modules for the future CMS tracker will be completed and yield modules that utilise the investigated advanced materials. During the funding period mass production will start, using the novel automated high-precision assembly techniques. This work will be carried in close collaboration with the interconnect experts.

In addition, the infrastructure available at the participating Helmholtz centres to carry out the proposed research and development programme will be further developed and extended.

3.2.1.4 Timelines of Activities and Expected Results

Years	Activity / Milestone	Participants
on-going - 2019	Characterisation and modelling of radiation hardness of sensors	DESY, GSI, HZDR, KIT
2015 -2018	Advancement of processing technology for high-Z and slim-edge sensors	DESY, KIT
ongoing - 2019	Development of large-area single crystal diamond sensors	DESY, GSI, HI JENA, KIT
2015 - 2019	Development of materials for fast and high-rate gaseous detectors	GSI, HZDR
2015 - 2018	Development of novel circuit architectures in advanced CMOS technologies	DESY, GSI, KIT

2017 - 2019	Development of technology for 3D-integration of readout ASICs	DESY, GSI, KIT
on-going - 2016	Creation of a common ASIC design environment and repository	DESY, GSI, KIT
2017 - 2019	Development of hybridization capabilities for rapid and low-cost prototyping	DESY, KIT
2015 - 2018	Development of construction technologies for ultra-light detector modules with advanced thermal and mechanical properties	DESY, GSI, KIT

3.2.2 Data Transmission and Processing

3.2.2.1 Challenges

Future detectors in the broader research field “Matter”, ranging from particle physics via nuclear and hadronic physics to materials research, will consist of anywhere from several million up to a billion electrical signal channels. Together with sharply rising rates with which the individual channels generate signals, this will result in a massive increase of the amount of data generated by these experiments up to and well beyond many hundreds of GBytes/s. The handling of this amount of data is one of the largest challenges for future detector systems. Increased bandwidth to transfer the data is a key element to solving this challenge. This however, only addresses part of the problem and will definitely not be sufficient. Additional methods need to be developed to process large data rates. For instance in many modern hadron and particle physics experiments, most of this data is typically only of immediate (on-line) value, and only a very small fraction is deemed sufficiently “interesting” to warrant storage for a more detailed analysis. In photon imaging on the other hand is it essential to store all measured data for detailed studies. In both cases, lossless data buffering and storage can be considered a prerequisite for proper scientific data collection. In order to match this prerequisite, the setup for pre-processing and the structure and timing of asynchronous buffer stages have to be determined according to the experiment’s requirements, thus bridging the asynchronous gap between data sources, concentrators and data storage devices.

The environment, the envisioned hardware has to operate in, can be completely different not only for different experiments but also even within the same experiment. For example radiation levels, available space, possibilities for cooling and data compression vary strongly from the inside to the outside of typical accelerator based detectors. Thus no singular approach to handle very high data loads is feasible but instead combinations of different approaches must be used.

Therefore, within this subtopic, three themes are pursued in order to address the salient issues at hand: The first theme “Tbit/s Optical Data Transmission” is devoted to the development of new optical data transmission methods, which allow the transmission of rapidly rising quantities of data. Within the second theme “Intelligent Programmable Electronics” advanced system architectures based on programmable hardware like FPGAs will be developed that enable high throughput data acquisition as well as online data pre-processing and reduction. Finally, in the third theme “Parallel Processing” highly parallel digital electronic architectures will be developed to realise user-driven ultra-fast algorithms on CPU or GPU clusters for fast processing, reconstruction and analysis mechanisms, thereby enabling for instance highly selective data filtering, online detector control systems and eventually feedback for user-driven analysis.

Tbit/s Optical Data Transmission

Even with massive local data reduction it will not be possible to transfer all raw data produced in a detector to the processing stages outside of the detector with electrical wires. Here optical fibres offer a 1000 times higher bandwidth (Tbit/s), lower signal attenuation, lower power consumption (pJ/bit), electrical insulation, and last but not least a considerably lower mass budget. Extremely power-efficient, electro-optical modulators are available in telecommunication research and should be adapted for use in advanced detector systems.

In today's detector systems directly modulated semiconductor lasers are typically used to transmit digital data. To this end, the output signals of the detector are digitized by a nearby Application Specific Integrated Circuit (ASIC) and converted to an optical signal by a laser-diode. In contrast to that, here non-modulated, continuous wave (CW) light will be generated remotely to keep power dissipation inside the detector to a minimum. The CW light will be modulated inside the detector and routed back to a receiver outside the detector. In a further step the modulators could be integrated monolithically together with amplifiers and other electronics. Such a scheme of data transfer is entirely novel to the field of complex detector systems and could revolutionize the approach for data transport and acquisition. With this technique, local power reductions and an increase of throughput per fibre by orders of magnitude are possible. The intended modulators are fabricated from silicon in a CMOS-compatible process and are able to transmit data rates of 40 Gbit/s per wavelength. With more sophisticated modulation schemes and wavelength division multiplexing a multitude of such channels can be transmitted through a single glass fibre. As a result, a considerable reduction of data cables and possibly power feeds and cooling pipes can be achieved. Consequently, less passive material is required inside the detector, thereby reducing the scattering of charged particles and improving the tracking resolution in particle and high-energy physics experiments. These improvements come at the price of a more sophisticated backend machinery, which is however outside of the fiducial volume

An alternative is analogue signal transmission. Here digital logic in the readout chip is avoided. The chip consists only of a simple circuit to adapt the detector signals to the modulator. The analogue-to-digital conversion of the detector signals is performed outside of the detector. With a suitable design of the modulator the adaptation electronics could be completely omitted for a sizable mass reduction. The modulator would then be controlled directly by the detector signals up to the point of a full optical particle detector. This approach would further reduce power consumption and mass and allows a continuously optimization of the analogue signal processing. This would open unprecedented opportunities in accelerator based or even cryogenic experiments.

Intelligent Programmable Electronics

Intelligent programmable electronics, like for instance systems built around Field Programmable Gate Arrays (FPGAs), combine the processing speed of dedicated electronics with the flexibility of software programs. FPGAs are the backbone of all modern data acquisition and processing systems from small laboratory setups, to midsize instrumentation at photon beamlines up to full scale accelerator based physics experiments where they are used as off-detector electronics. Here the vast increase of incoming raw detector data of many 100 GBit/s and higher and the required sophisticated on-line processing of the data lead to a corresponding increase of the complexity and size of infrastructure of such systems. As a consequence design complexity and thus the development costs and times are rising drastically. To face this challenge an even closer collaboration of the cooperating centres, universities and international partners is required.

One way to deal with the massive increase in data rate is data reduction as close as possible to the source. However, at the same time the criteria to select the interesting data out of all samples are getting more and more complex. As a result, large bandwidth and processing power very close to the detector is required. Intelligent programmable electronics would be the ideal candidate for this purpose. For applications in particle, nuclear and hadron physics experiments it would be necessary to increase the radiation tolerance of these components in a way that they can withstand the hostile environment close to or even within the detector. The high frequencies needed for processing and transmitting digital data close to the sensitive detector elements on the other hand cause a rising challenge to shield effectively the analogue signals from digital crosstalk. Electromagnetic interference related couplings on module and system level have to be investigated carefully. This difficulty will get even more pronounced with the usage of 3D-ASICs where the granularity and the sensitivity of detectors are significantly increased.

The capability of optical links to transmit analogue information from the detector offers the possibility to implement another scheme for data processing. Here the electronics close to the sensor would be reduced to a pure analogue stage coupled to an optical modulator. The analogue signal is then transmitted to the DAQ system for the digitization and processing. Here radiation tolerance is a smaller problem but the amount of data to be transmitted might rise even more and data processing is still required.

The challenge of data collection, reduction and transport close to the detector is thus to be addressed by three approaches: The first approach foresees application specific electronics close to the detector, a fast optical link for data transmission and sophisticated off-detector data processing. The second scheme puts programmable electronics as close as possible to the detector to reduce the transmitted data load. In the third approach the detector data is transmitted analogue to be digitized and processed later. The research within this subtopic aims to enhance substantially the performance of all these approaches and thus to enable better science. Which path is then chosen for a given experiment depends on its specific environmental boundary conditions.

In addition to the uses mentioned above, FPGAs can additionally be employed as front-end electronics (FEE). Taking advantage of the state-of-the-art semiconductor processes deployed in FPGAs, it is possible to implement functions like Time-to-Digital converters (TDCs) in FPGAs with a time precision better than 10 ps, which was previously available only by dedicated ASICs. This has a huge potential for applications in virtually all particle and nuclear physics experiments and many photon science and medical applications like PET imaging. Furthermore, the integrated fast discriminators inside FPGAs allow both the power dissipation and the cost to be reduced for applications with a high number of discriminators (e.g. readout of photo-multiplier tubes) while still relying on commercial electronics with all their benefits compared to ASICs.

Parallel Processing

After transfer of the data away from the detector itself, a two-fold challenge of fast data analysis arises: First, for some applications the amount of data acquired in a certain time interval is too large to be stored permanently. These applications require the online reduction of data by compressing, filtering or converting the data. The second class of applications requires fast reconstruction algorithms, for direct feedback to the measurement and potential control by the user.

With the development of advanced multi- and many-core computing systems, high bandwidth and high computational performance have become available that allow implementing data reduction techniques in software rather than hardware. This offers an even higher flexibility compared to programmable hardware, enables the implementation of more sophisticated algorithms, easy adoption to the demands of specific applications and finally the realisation of high resolution applications. The choice of the parallel processing hardware, whether FPGAs as in the previous theme or GPUs/Multi-core systems as pursued in this theme will depend upon details of the tasks to be performed and the experiences of the available staff. Thus, this subtopic pursues both technological solutions in order to identify which is most appropriate for a given application. Looking at the whole experiment, the data acquisition will require a heterogeneous solution utilizing the programmable hardware and software building blocks developed in this topic.

Classic data reduction techniques, which rely on simple yet fast hardware-based selection, can be replaced by fast, sophisticated selection algorithms as the selection criteria become more complex. This in turn requires the primary data to be kept for longer, albeit limited times while performing online selection on streaming data. This approach should accommodate for future increases in data rates, so that the algorithmic implementations have to be scalable to large compute farms. The challenge will be to optimally distribute the data to the compute cores to keep throughput as high as possible.

For real-time analysis of complex data, fast state-of-the-art hardware will be used. The ultimate aim is to provide user-driven data analysis that will enable the user to assess the quality of the data, help to select the relevant data, store it in an optimum representation and steer the data analysis process. Ultra-fast data reduction and analysis algorithms specifically tailored to experimental needs can be implemented on general purpose, high bandwidth hardware. Thus best practices and optimum solutions can be shared, making use of the hardware most suitable to the task at hand. In conclusion, we foresee to implement data reduction, filtering and extraction of meaningful data on all levels of the data chain. The division between data acquisition and analysis vanishes, allowing for flexible, adaptable and scalable solutions specific to each application.

3.2.2.2 Current Activities and Previous Work

In this section a brief overview of our previous and current work related to the scope of data transmission and processing for detector applications will be presented. For the theme of Tbit/s optical data transmission different types of silicon-based optical modulators were developed for performance, for stability with respect to environmental influences, and for radiation hardness. Several designs in different fabrication technologies have been created and ordered for production to be able to select the technology that best suits the needs of the experiments. To parallelize the optical modulators and use wavelength division multiplexing on glass fibres, low-loss wavelength splitters and combiners on Silicon-on-insulator wafers were designed, simulated and brought to fabrication.

Major building blocks for the transition from current DAQ systems to new architectures with digital pre-processing in the front-end and high-speed serial interconnects to massively parallel compute farms are being developed or evaluated.

The exploitation of the full power of FPGAs in modular board systems requires the replacement of classical parallel backplanes by high-speed serial backplanes. In this field, MicroTCA is one of the emerging technologies originally developed by the industrial consortium PICMG for the needs of the telecommunication industry. MTCA.4 is an extension for I/O bound applications in science and industry developed under the leadership of DESY together with research labs and industrial enterprises. MTCA.4 is extensively utilized in DAQ and control systems for FLASH and XFEL. It will play an essential role for FAIR detector systems. It is also utilized for the standardized real-time feedback needed for the stability, controls and synchronization of the accelerator components in the programme topic ARD. The Helmholtz Validation Funds support the commercialization and application of MTCA.4 in industrial enterprises and other large-scale research projects. The project costs of about 4 M€ are shared between the Helmholtz Association, DESY and partners from industry.

A first prototype of the Helmholtz AMC, a versatile, MTCA.4 compatible module aiming at data acquisition applications with data rates in the range of 50 GBit/s was developed at DESY with contributions from KIT (Figure 25). Key features of the FPGA based (Kintex7) board include standard high-speed serial interfaces for inter-crate and external communication like PCIe, four 10G-Ethernet links and support for up to 8 GByte of DDR3 SODIMM memory. The current prototype is designed to allow for future enhancements of processing power and data throughput. Application and detector-specific extensions and adaptations like ADC modules can be connected via dedicated rear transition modules (µRTM). Firmware development is undergoing at DESY and KIT with the goal to provide a user framework that allows concentrating on application-specific algorithms and using the interface to the board's infrastructure as an IP unit.

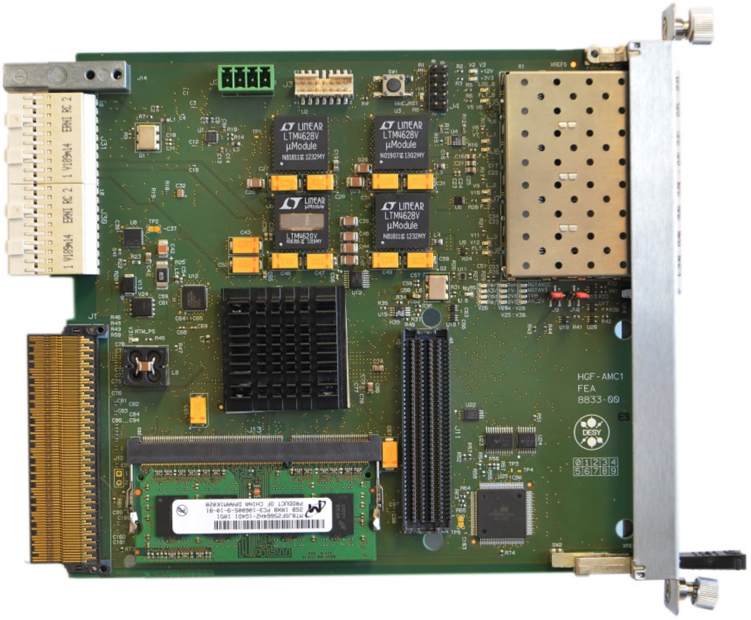

Figure 25: First prototype of the Helmholtz AMC module for data acquisition applications

The Helmholtz AMC will next be integrated in a framework for fast data acquisition, data transport and real-time data processing for synchrotron applications currently under development at KIT. First applications focus on X-ray radiography, tomography and laminography within the Ultra-fast X-ray Imaging Project (UFO). Here, a workflow connecting high-throughput detector readout via FPGAs to accelerated image reconstruction via GPUs is being developed. Fast real-time image processing offers the opportunity to realise high-throughput image-based control loops. GPUs for scientific computing have been successfully applied to other fields like image correlation techniques for contact-free measurements in material science and fast reconstruction of a novel 3D ultrasound computed tomography (USCT, see also “Technology and Society”).

Another application of the Helmholtz AMC board is the readout of the PANDA Micro Vertex Detector and the Straw Tube Detector which are currently under development at FZJ. In this context the time synchronization potential of the XILINX Kintex7 transceivers is under study, a PCIe uplink module with 10 GBit/s is being build and FPGA-based algorithms for the feature extraction of Straw Tube signals, including cluster identification, dynamic baseline adaption and pileup unfolding are under development. In addition, a small laboratory DAQ system, based on a XILINX Virtex6 evaluation board, was developed and can easily be adapted to different types of front-end ASICs. It is presently used for the readout of various PANDA front-end prototypes.

In order to guarantee the broad applicability of the new Helmholtz AMC framework, the developments will also include biology (development of a PET for plants) and Neutron scattering (wavelength shifting fibre detector).

Fast parallel online reconstruction algorithms for PET and prompt gamma imaging are in development. Similar to the activities within the UFO project, phase retrieval algorithms for Small-Angle X-ray Scattering (SAXS) images have been implemented for GPUs and multi-core CPU hardware. Under study is the feasibility of using SAXS at XFEL to probe femtosecond plasma dynamics in the interaction of a high-power laser with matter at a similar density to ground state solids. Common activities include the development of scalable workflows for online data analysis and the optimization of reconstruction algorithms on many-core hardware such as GPUs. HZDR has proven expertise in developing scalable algorithms for large-scale compute systems up to several thousand GPUs. In-house developments can make use of 68 NVIDIA Kepler K20 GPU compute nodes and 88 nodes with four 16-core AMD CPUs each, interconnected via FDR infiniband. These activities also relate to the research programme MML and are integrated within the Dresden NVIDIA CUDA Centre of Excellence, a joint centre of

Helmholtz-, Max-Planck and Fraunhofer institutes headed by the Centre for High Performance Computing of the Technical University Dresden (ZIH). It fosters interdisciplinary exchange on the optimization, scaling and performance analysis of algorithms for GPUs and offers workshops, trainings and university teaching modules on many-core parallelization techniques as well as access to test hardware and compute cluster resources.

These activities connect well to the usage of GPU clusters for fast online track finding and fitting algorithms for the online event filter of the PANDA experiment. Curved tracks have to be found in real-time from a continuous stream of data originating from subdetectors with strongly varying time and point resolutions. Various algorithms are currently under development and optimization together with the NVIDIA Application Lab at Jülich. Since 2012 NVIDIA and the Jülich Supercomputing Centre (JSC) jointly operate the NVIDIA Application Lab at Jülich and enable scientific applications for GPU-based architectures, provide support for their optimization and investigate performance and scaling.

Since the establishment of the “Detector Technology and Systems Platform” the level of communication and collaboration between the participating centres has drastically improved through topical workshops, regular telephone conferences and a common project database to share FPGA projects.

3.2.2.3 Objectives

Tbit/s Optical Data Transmission

The main objectives of this theme are the design and miniaturization of modulators as well as the examination and improvement of their radiation tolerance. Further examinations include environmental tests for low temperatures and high magnetic fields. For analogue transmission the resolution, accuracy, noise immunity and temperature stability will be examined. Subsequently the modulators should be combined with ASICs and later monolithically integrated. To increase integration density, design concepts with multiple modulators and associated waveguide components (e.g. wavelength division multiplexers, combiners, phase shifters, fibre couplers) will be developed and realised. Finally, a multi-channel, monolithically integrated readout chip will be realised with optical output as well as a modulator directly connected to a detector without adaptation circuitry.

For system integration a further focus is put on a reliable, compact and low-mass coupling between the fibre and the chip, suitable for use in detector environments. The main objectives are material selection as well as mechanical design to ease fabrication, to maintain operation over a large temperature range and in strong magnetic fields, and to safely handle the fibres.

In the first half of the PoF-III period a silicon-based electro-optical modulator will be developed to withstand radiation, low temperatures and strong magnetic fields. This modulator will be advanced to a multi-channel modulator chip with integrated wavelength splitters and combiners.

A further goal at the end of the PoF-III period is the monolithic integration of driver electronics on the electro-optical modulator chip. A compact fibre-chip coupling will allow the use of the modulator chip in detector systems with tight space and mass constraints.

Intelligent Programmable Electronics

The rising complexity of DAQ systems causes a significant increase in development time and costs. Therefore it is crucial to exploit synergies provided through definition and use of interfaces and platforms. This way hardware, firmware and software can be exchanged more easily.

The Helmholtz AMC platform combines development activities inside “Matter” to shorten development cycles and reduce the costs of new systems. The next step is to put this system to test and expand it to a broad application base. A modular system platform of common firmware and hardware building blocks will be assembled, including standardized interfaces, common IP cores and hardware boards. These developments support a multitude of applications from photon science to particle physics. As a concrete example it is planned to use them for the PANDA Event Filter, the CMS Track Trigger and real-time data processing for synchrotron applications.

An essential functional block is the development of a versatile buffer and storage system for lossless data recording. One of the main issues here is the inherent asynchronous operation of data sources and the corresponding concentrators and data storage devices. This buffering scheme has to adapt to varying rates of the multiple data sources and sinks while synchronizing multiple data streams at highest possible bandwidth. A versatile management of data entities and buffering schemes along the data transfer path will foster the capability to adapt to different experimental setups. The result will be a reliable data path for the whole detector system with high speed and throughput.

The results of the different development projects like IP cores, hardware descriptions and software packages will be made available for the participating institutions via an open database to minimize parallel developments and bring together different developer groups. Moreover the very successful series of topical workshops will be continued to maintain and further stimulate knowledge exchange and networking inside “Matter”.

Another complex enterprise is the implementation of the Tbit/s optical links from the first theme in complete readout systems. This requires significant development work on the hardware as well as on the firmware side. A first step is to improve the fundamental understanding of electromagnetic interference related couplings on the module- and system-levels for future detectors with high requirements on analogue sensitivity, data rates and power consumption. The layout techniques for PCBs have to be improved in order to increase the allowed data rates stepwise from 10 to 25 and finally to 40 Gbit/s on differential pairs. The Tbit/s optical data stream is then divided into the differential pairs. In parallel, firmware development techniques will be developed, which are able to cope with the much tighter timing constraints for high frequency data processing.

The new approach to use FPGAs as a TDC for analogue data opens up a wide field of possible applications with a huge potential to reduce production costs and time. The recently developed precise TDC-in-FPGA technology can even be extended to applications beyond pure time measurements. In many detectors precise charge information is needed. These Charge-to-Digital-Convertors (QDCs) and Analogue-to-Digital-Convertors (ADCs) can be realised with comparably simple analogue FEEs together with the existing TDCs that achieve 10 ps time resolution. The goal is to build the necessary FEE in combination with the discriminators and TDCs in FPGAs to produce QDCs with better than 0.5% charge precision. At the same time the TDC-in-FPGA will be optimized further to allow for leading and trailing edge measurements in one channel, thus doubling the usable number of channels for Time-over-Threshold applications.

Parallel Processing

Data analysis capacities will increase significantly with future compute hardware. For numerous applications real-time data analysis and visualization for the user should be integrated with the data acquisition process. Examples include the data analysis for the ANKA X-ray images and SAXS images for the Helmholtz beamline at XFEL, event analysis and selection for PANDA and CMS and image reconstruction for online dosimetry. The integration of user control into the data acquisition for imaging applications is an important goal and requires fast reconstruction algorithms. At the same time, the requirements for scalability of the algorithms in particle and nuclear physics applications are also of interest in X-ray imaging with respect to the high data rates foreseen at XFEL. The objectives thus reflect the specific data chains of each application but highlight possibilities for common developments.

As the first objective it is foreseen to identify and assess fast data analysis hardware that is either available at the institutes or commercially and that best suits the needs of the experiments. This is accompanied by the identification, comparison and validation of existing algorithms for data analysis and followed by the development and optimization of these algorithms and the creation of new algorithms for parallel data analysis. As an example, algorithms initially developed in imaging are also of interest when finding tracks in particle detectors. For this objective the challenge is to develop versatile algorithms that are easy to implement on a variety of hardware platforms.

After this assessment and testing phase, the second objective is to implement the algorithms on the selected hardware according to the needs specific to each experiment. This will involve the measurement of code performance and scalability and will require the use of both on-site and off-site compute clusters. Here we will profit from the support of organizations such as the NVIDIA Application Lab at Jülich and the CUDA Centre of Excellence in Dresden.

With the algorithms in place on each level of data flow, they have to be interfaced for pipelining and connected via workflows. The second objective, the integration of algorithms into an analysis pipeline, thus focuses on a demonstrator and prototypical applications. There already exist prototypes for PET image reconstruction at HZDR and X-ray imaging at KIT. Mutual exchange of best practices between these prototypical installations and the demonstrator setup detailed later is foreseen. This will enable testing and optimizing data transfer methods for throughput and make an evaluation of the algorithmic performance in real world environments possible.

All developments will be made available via a common technology platform. This platform will provide computational resources and programming environments for the next generation of programmable hardware. It will incorporate workflows for data acquisition, transfer, analysis, quality assessment, feedback and interaction with the user. Here the challenge will be to define open interfaces between the software components that are scalable with increasing data rates and number of data streams. This is of special importance for possible exchange with projects within the programme MU and HDRI in MML, since a common platform greatly facilitates the use of standardized interfaces.

The development of high-throughput, parallel algorithms for reduction, filtering and online analysis of data require both combined development efforts and optimization for specific experiments. For example, in imaging applications only a few filtering steps are usually employed before the compute-intensive reconstruction step, while in particle and nuclear physics a large hierarchy of online and offline filters is applied to consecutively reduce the amount of data. Each application will therefore have its specific data transfer and selection hierarchy, while certain hardware and software developments can be shared and made to scale. The critical point here is to ensure for these algorithms to execute concurrently. Thus it will be an objective to optimize data transfer for streaming data by parallel, asynchronous communication, realizing optimum throughput.

DAQ Demonstrators

In PoF-III the implementation and optimization of fast reconstruction algorithms on multi-core hardware and programmable hardware and their integration into a common technology platform is foreseen. In order to identify the most important challenges as early as possible, systems prototypical of real applications will be designed.

In order to demonstrate the basic building blocks a twofold strategy is followed: small scale prototype applications such as UFO at KIT and PET image reconstruction at HZDR and FZJ will be realised in parallel to two large-scale demonstrators, thereby combining rapid prototyping and testing with the long-scale development of integrating the many technologies developed. These prototypes allow for testing critical parts of the data pipeline on a shorter time scale without the need of a complete demonstrator in a real-world environment. Thus, progress on these smaller prototypes will accompany the development of the demonstrator, providing many opportunities for the exchange of ideas, best practices and implementation optimizations. In addition, some capabilities such as online user feedback to the DAQ system that are not part of the complete demonstrator can be implemented in the small-scale prototypes. Clearly, a large-scale demonstrator is the best test for scalability. Nevertheless, scalable workflows can already be explored with the small prototypes. For example, X-ray imaging will surely demand scalability once XFEL is operational, however small-scale sources exist today that allow a prototype analysis pipeline to be implemented. It is important to follow a variety of approaches towards scalability: individual events have to be analysed in parallel for large-scale detectors, requiring the timing information for each event. On the other hand, photon science and imaging applications are based on time-integrated photon signals or images, delivered at a high rate. In the first case, the technology must scale with the rate of events belonging to a single signal, while in the latter case the technology developed must scale with the image rate. Activities within HDRI and MML that face similar challenges will open the possibility of mutual exchange of ideas and best practices.

Possible candidates for a large-scale demonstrator are FAIR experiments like PANDA and CBM as well as the silicon detector readout and track finding electronics for the HL-LHC. Similar to the planned upgrades of LHC experiments, which operate at a fixed bunch crossing rate of 40 MHz, PANDA and CBM will operate with a stochastic interaction rate far beyond 10 million events per second. Due to the complex selection criteria, these experiments have to run in a continuous mode with no first level hardware trigger. As a consequence there must be an extremely powerful online event filtering system, requiring a high computational complexity since tracks are non-linear in many cases. Due to the complexity and extreme performance requirements of the event filtering system data acquisition has to be organized into individual layers with different technologies on each layer:

a) Front-end electronics, typically ASICs, are based on continuous signal sampling, which requires self-triggering capabilities and local intelligence in order to do pulse detection, feature extraction and noise or zero suppression.
b) Local concentrator systems with buffering capabilities have to provide very effective, but simple selection mechanisms while a distributed farm of FPGA-based hardware has to do event forming and more complex filtering decisions.
c) Event selection mechanisms of highest complexity have to be based on a farm of processor-based nodes, which are supposed to be GPUs.

Equally challenging DAQ requirements arise through the extreme track densities at the HL-LHC. Here it is the key to include the vast information of the silicon trackers into the lowest trigger level and obtain a trigger decision in ~10 µs. This again requires massively parallel digital hardware, possibly novel architectures and heavy use of content-addressable memories, and fast but complex filter algorithms.

Due to the extreme performance requirements at both FAIR and HL-LHC, there is very significant overlap in the technological solutions based on emerging new hardware technologies like MicroTCA and ATCA.

The planned demonstrator for FAIR combines the three different themes of this subtopic into one project. It will be realised in three stages. In the first stage the appropriate hardware is developed based on the Helmholtz AMC system and the low level FPGA-programming is done. This system will be connected via standard optical links. In the second stage more sophisticated algorithms will be developed for a fast pre-processing of the incoming data stream and the connection to a farm of processor-based nodes will be done. In the third stage the demonstrator will be connected to the high-speed optical links developed within this subtopic once the hardware is available.

The DAQ and track finding demonstrator for HL-LHC will use the same technologies as above, complemented by associated memory blocks. Both demonstrators will be produced with national and international partners in the context of specific experiments. The Helmholtz centres participating in both demonstrators will exchange information, share technologies and exploit the numerous synergies in common hardware platforms, optical links, firmware for track finding, etc.

3.2.2.4 Timelines of Activities and Expected Results

Years	Activity / Milestone	Participants
2017	Realisation of a multi-channel, silicon based electro-optical modulator	GSI, KIT
2017	Realisation of small scale DAQ prototypes for photon detection and user-driven imaging	DESY, FZJ, HZDR, KIT
2017	Development of the common technology platform based on Helmholtz AMC for DAQ, throughput-maximized data transfer and distributed data analysis	DESY, GSI, HZDR, FZJ, KIT
2018	First DAQ and event filter demonstrator based on the common technology platform using streaming data input for FAIR experiments	DESY, FZJ, GSI, KIT
2018	First DAQ and track finding demonstrator based on the common technology platform with content-addressable memories and TCA technology for CMS	DESY, KIT
2019	Prototype of an integrated electro-optical modulator and electronic driver chip	DESY, GSI, KIT
2019	Proving scalability of the DAQ demonstrators using CPU/GPU clusters	DESY, FZJ, HZDR, KIT

3.2.3 Detector Systems

An important aspect of detector R&D in experimental physics is the design of the detector as a complete and integrated system; modern detectors are more than the assembly of their bits and pieces. The process of system integration is central to bridging the gap between fundamental technological developments and their application to concrete problems in experimental science. This subtopic is intended to address just this issue: to test the underlying technologies developed in subtopics one and two in a fully functional detector system. It will make it possible to identify and explore a number of architectural options for specific experimental challenges in the field.

3.2.3.1 Challenges

The ultimate goal of detectors in the research field “Matter” is the detection of charged and neutral particles, together with the measurement of their properties. Depending on the particular experimental application, very different detector types in broadly varying configurations and even complex assemblies of several detector types are needed.

Modern and future accelerators along with research facilities produce increasingly higher particle intensities. Together with the increased event complexity, this poses a continuous challenge to detector capabilities. Novel technologies are essential to enable progress in the field. These are addressed in subtopics one and two through the development of new sensor materials, integrated readout electronics as well as data transmission and processing capabilities. However, without the seamless interplay of these ingredients and scalable concepts that make it possible to create, integrate and control large systems and the data generated, these challenges cannot be adequately met. Thus, novel technological solutions find their ultimate test in their implementation in a fully functional detector system, ready for use in a realistic environment.

In this subtopic, key technologies are investigated and integrated into prototype detectors. To this end, know-how that was explored and made available within subtopics one and two is brought together with the focus on system design. The detector systems that will be developed were chosen because they present a broad range of design challenges that will often occur in the coming years. The prototypes will be used to perform proof-of-principle experiments. Based on these results, the technologies will then be made available to further experiments, performed within the research field “Matter” and beyond. In parallel, the experience gained will be fed back to subtopics one and two, so as to steer the technological developments towards maximum applicability. Series production for any full detector system is not included in this subtopic but will be done in the relevant research programmes e.g. “Matter and the Universe”. The development of demonstrator modules or automated assembly techniques on the other hand is part of DTS.

The types of detectors were strategically chosen to address the main challenges of the research field – that is, the detection of photons and of all kind of charged particles ranging from minimum ionizing particles (MIPs) to highly ionizing particles. Moreover, with the future projected high-rate experimental setups on the horizon, a common effort to boost rate capability by an order of magnitude or more is needed and will be addressed within this work package. Technically, the systems cover fast photon and X-ray detectors, gaseous detectors, fast timing detector systems, monolithic CMOS imagers as well as the Helmholtz-Cube. The Helmholtz-Cube plays a special role for this topic in that it serves as a versatile platform for the creation of practical systems with a variety of different pixelated sensor technologies and as a test platform for data transmission and processing developments.

3.2.3.2 Objectives

The main objective of this subtopic is the development, design and construction of several prototype and demonstrator detector systems based on advanced and cutting-edge technologies. The prototypes will be developed and integrated towards a point where they can be proposed as a viable detector solution for full scale experiments. A number of concrete systems have already been identified, and are explained below. It should be mentioned that this is a starting point. The subtopic will maintain the flexibility to react to newly appearing developments and opportunities throughout the funding period.

Helmholtz-Cube

Photon counting hybrid pixel detectors are the detectors of choice for photon science at synchrotron storage rings and are considered as the next system in medical imaging. They offer the advantage of “zero noise” needed for low flux measurements and are able to cope with high fluxes by being able to handle large counting rates exceeding 10^6 Hz per pixel. The same criteria hold true for many particle and nuclear physics detector applications as well, although the amount of material of hybrid detector systems often impedes their use in tracking applications. For Free Electron Lasers (FELs), hybrid pixel technology can be used to build integrating detectors with extreme dynamic ranges and high frame rates.

The hybrid structure makes it possible to couple a variety of sensor materials to the same readout ASIC. Thus, the same system can easily be adapted to different photon energies or even charged particles such as protons, electrons or other minimally ionising particles.

One such modular hybrid pixel device is being developed within the Helmholtz Detector Technology and Systems topic: the Helmholtz-Cube. It is currently used to integrate novel, alternative sensor materials to form a complete hybrid pixel device. It will further be elaborated and exploited as a test bench for hybrid detector system concepts. The Helmholtz-Cube currently has a pixel size of 55 µm, in order to combine high-resolution imaging with a high frame rate for measuring fast dynamics, and a tileable design to allow the construction of larger systems.

Within this activity the Helmholtz-Cube will be employed to build a large area X-ray imaging system for synchrotron beamlines. The goal is to construct a 10 x 10 cm^2 imager, with more than 2 megapixels, running at a sustained rate of 4000 frames per second. Initially, a system will be built with silicon sensors for detecting moderate energy X-rays. To address hard X-rays, one system will then be realised with a GaAs sensor, and another with a CdTe sensor. Other developments from subtopic one, such as slim-edge sensors and through-silicon-via technology, will likewise be integrated into larger systems.

The Helmholtz-Cube may also be employed for charged particle detection. In particular, interchanging the sensor material with e.g. CVD diamond would provide a system with extreme radiation hardness. For applications like Proton Radiography (PRIOR at FAIR/GSI), where such a device could be employed for direct imaging of the spatial proton distribution, it is then the gating capability rather than the overall frame rate which will need to be optimized.

The Helmholtz-Cube serves in addition as a vehicle for implementing and testing modern data transmission and processing technologies in the subtopic two. Within this topic, the Helmholtz-Cube is a fully functional detector system for the use at synchrotron beam lines. Nevertheless, other applications may also be explored, possibly beyond the Program Matter or even the Helmholtz Association.

Compact Gaseous Detectors

Gaseous detectors have extensive use in scientific research and beyond. They offer adequate and mature solutions in particular for applications in which large areas and flexible geometries need to be covered. Enormous volumes of up to e.g. 90 m^3 (ALICE TPC) can be instrumented with excellent spatial resolution at a low number of detector channels and a minimum amount of material.

Over the last fifteen years, a fantastic portfolio of micro-structured amplification and readout concepts has been developed and is still evolving rapidly. Examples are devices based on Gaseous Electron Multipliers (GEM) or Micro-Mesh Gaseous Structures (MM). These devices boost rate capability and resolution to a level where gaseous detectors can even compete with silicon-based devices. At the same time, they do not suffer from effects which spoil the energy resolution at high levels of energy deposition. So, they can easily adapt to the high dynamic range of primary ionisation that ranges from MIPs on one hand to the heaviest ions.

Various industrially available micro technologies can be exploited. While gaseous detectors traditionally had to rely upon tedious manual assembly and manufacturing processes, highly automated industrial processes such as lithography or even CMOS technology can now be exploited for ever higher granularity together with cost effective integration of the readout electronics. Indeed, this may be essential for FAIR, HL-LHC as well as ILC and CLIC. With built-in variable-gain amplification stages the signal dynamic range may be adapted to the dynamic range of available integrated readout electronics.

The construction and test of fully functional systems is key: Access to and know-how on these technologies will be available through this topic. As an example, pixelated CMOS devices - of the hybrid type or monolithic - may be exploited as a signal interface to electronics for these advanced gaseous detector systems.

An important member of the family of gaseous detectors is the resistive plate chamber (RPC). It relies on an immediate avalanche signal surge that entirely decouples signal amplitude from the amount of primary charge and thus allows for timing performance on the order of ten to hundreds of picoseconds. These large-area economical devices play the essential role of the “stop”-generating detector in time-of-flight (TOF) systems of modern complex experimental setups. Here the challenge is to provide an adequate quenching mechanism that balances rate capability and system stability. One goal within this subtopic is to set up a complete, cutting-edge RPC system where timing properties and rate capability, often compromised in system operation, may be tuned to the upmost performance.

In general, concerning gaseous detector technology, little system-relevant know-how may be inherited from industry. As a consequence the entire know-how on system engineering, quality assurance and ageing properties linked to gaseous detector technologies needs to be maintained and pushed forward within the scientific community itself. DTS is a most important vehicle to this end.

The participating centres can look back upon a long history of gaseous detector developments, large system design and construction. They seek to develop robust and scalable micro-patterned readout structures for gaseous detectors in timing, trigger and tracking applications in the form of ionisation chambers with no gain, TPCs, trackers and RPCs. Unprecedented granularity will be achieved exploiting a Timepix/Medipix-based readout. Those systems will especially be optimised in terms of their mass, rate capability and spatial resolution. Finally, one additional aim is to develop and implement resistive detector structures especially for high-rate and high ionisation environments and thus improve operational stability.

Fast Photon and X-ray Detectors

Silicon Photomultipliers (SiPMs) are fast silicon-based pixelated photo-diodes with intrinsic amplification and spectral sensitivity from the optical to the soft X-ray domain which may likewise be used for the detection of charged particles.

The technology is rather new – the first devices became commercially available in 2007. It quickly attracted attention in a broad range of applications, from astroparticle physics, particle and nuclear physics to photon science, medical imaging and security surveillance. With their insensitivity to magnetic fields, SiPMs more and more replace conventional photo-multipliers in scintillation detectors currently being constructed or conceived for accelerator based experiments. The demand for smaller pixels, larger dynamic range, higher fill factors, larger surfaces and lower noise is driving the development pursued by partners in industry and in the Max Planck Society.

Modern 3D interconnection technologies can be used to integrate the sensors with their readout electronics and thus open up these detectors for yet other applications, for example as track detectors or beam monitors with intrinsic signal amplification and individual pixel readout.

Whereas the first generation of SiPM technology provided analogue signal output with a single output channel for many pixels and consequently the loss of position information, current developments drive towards a direct digital per pixel interface (digital SiPM). With individual pixel readout the sensor becomes an imaging device with intrinsic amplification. This expands the field of application of this sensor technology beyond pure photon detection to charged particle tracking, as needed in nuclear and high energy physics. With 100 ps time resolution they are also suitable for time-of-flight and Cherenkov detectors, where they provide superior pile-up rejection capabilities in high background environments, as found e.g. in astrophysical applications. Finally, digital SiPM technology promises to eliminate the intrinsic temperature sensitivity of analogue SiPM technology and provide better noise control.

SiPM developments have already led to a break-through in calorimetry as well as positron emission tomography, to name two examples of active research at DESY. Several efforts towards the digital version have been started by industry (Philips) and academia (Delft University) in the past years, but a full imaging device does not yet exist. Within this activity a clear path has been set out to proceed via a sequence of prototypes towards higher levels of integration, finer pitch (resolution or dynamic range), higher sensitivity and larger area.

The strategic goal of this activity is to establish SiPM technology – digital or analogue. It will be achieved through the realisation of fully functional systems that will then prove the technology´s breadth in practical applications within the research field “Matter”, the Helmholtz Association as a whole and beyond.

Fast Timing Detector Systems

Time resolution and high rate capability are key detector properties for many detector applications. Unfortunately, there is often a trade-off between improving these properties and achieving a high signal-to-noise ratio or a high dynamic range. Along with the ever growing signal rate, the requirements concerning the radiation hardness of sensors and front-end electronics increase steadily.

Important applications of fast timing detectors are, for instance, fast tracking and time of flight (TOF) detector systems for current and future experiments with unprecedented high-intensity beams or the detection of coherent synchrotron pulses at next generation synchrotron light sources and XFELs. In these applications each of the system components presents technological challenges: the quality of novel sensor materials, signal formation, data transmission and processing, the transmission of high-bandwidth pulses over long distances and finally the acquisition and handling of huge amounts of data in multi-channel systems. Two demonstrators of a fast timing detector system will be built: one based on CVD-diamond sensor material and one based on the high-temperature superconductor YBCO.

To obtain a radiation-hard and fast alternative to silicon sensors, the CVD-diamond sensor technology will be combined with multi-channel microwave microelectronics adapted to the ultra-fast but comparatively weak diamond response to MIP interactions. Thin-film high-temperature superconductors such as YBCO offer even better time resolution, due to their very fast electron energy relaxation time, combined with excellent linearity and large dynamic range. A first ultra-fast system including superconducting YBCO sensors, wide-band low-noise amplifiers, a fast pulse sampling board and FPGA-based back-end electronics has been produced and proved extremely useful in the characterization of coherent (Terahertz) synchrotron radiation. Systems based on NbN and zero-bias Schottky diodes are also available. So far, such systems are based on a single channel and their performance is limited by the use of very high bandwidth but discrete electronics. If expanded to become a multi-channel pixelated detector system, the cryogenic bolometer prototype will introduce a new technology into nuclear physics, particle physics and photon science. An entirely novel detector principle for extremely fast applications may evolve.

The goal of this activity is to explore the enormous potential of new sensor materials allowing for large area devices, 3D sensor structures, 3D interconnection and broadband multi-channel ASICs, in order to realize novel, fully operative systems of extremely high timing performance. In view of upcoming FAIR and HL-LHC applications, these may eventually serve as radiation-hard, ultra-fast alternatives to silicon devices in specific timing applications, such as beam-condition and spill-monitors, for the detection of synchrotron pulses or as an in-beam start detector.

CMOS sensor systems

CMOS imagers have been steadily on the rise for the past decade or more. They directly and fully profit from the advances of industry in CMOS technologies in general and CMOS imager technology in particular. CMOS imagers can combine charge-sensitive pixel arrays with highly integrated electronics in one monolithic piece of silicon, reducing readout complexity as well as mass. Compared with CCDs, CMOS imagers hold the inherent promise of faster operation, larger full wells and less pixel-to-pixel interference. Compared with hybrid pixel assemblies, monolithic sensors are of very low mass, especially when thinned to the thickness of their active detector volume and the underlying electronic circuits. With everything integrated into the silicon, they even provide easier access to yet finer pixel pitches, which is limited by the interconnect technology in hybrid devices.

On the other hand, these monolithic devices rely entirely upon the standard options prescribed by industry for the particular process within CMOS technology. Thus, the thickness of the active detection layer, the epi-layer, is predefined to approximately 20 to 50 µm of epitaxial silicon. This thickness then determines the quantum efficiency of the devices, the fundamental property of any detector.

CMOS imagers find applications for (softer) X-ray imaging at high frame rates and with high dynamic range at synchrotrons and FELs as well as in inner tracking detectors in nuclear and particle physics experiments like CBM at FAIR or the ALICE upgrade. As readout devices for primary detectors producing light or charged particle output (e.g. scintillators) their application range is even wider. An example of this is proton radiography, where CMOS imagers find employment in high frame rate gated camera systems that image the primary scintillator plate.

For the typical photon and X-ray applications, the image is accumulated from many individual photon interactions within the sensor. The image intensity integrated over a certain, often specifically defined, window in time carries the scientific information. Here, the technological challenge is to achieve a high frame rate, low-noise and high shutter quality in terms of speed and image leakage. For the typical tracking application, however, individual signal counting rather than integration would be preferable, as the signals are to be extracted event by event. In practice, tracking applications like the CBM-MVD or the ALICE ITS upgrade profit from the push towards higher frame rates since the event based readout is yet to be addressed in monolithic CMOS sensor developments, and this at least reduces the number of superimposed events in a single image. Also, the activities on back-thinning, driven by soft X-ray imaging applications, align perfectly with the needs for ultra-low mass in tracking applications.

The vision from the nuclear and particle physics applications perspective is a CMOS sensor system that allows for individual event-based and time-stamped pixel readout. Likewise, for storage-ring based photon-science experiments such a system would eventually allow the assignment of individual photons to a particular electron bunch and thus enhance time-resolution to a level limited by the bunch length only.

The objective within this activity is to develop and construct high-frame rate, back-thinned CMOS imagers. This covers both the design activities as well as the post-processing steps like back-thinning or back-side processing. The developments will be driven by realising a large-area, monolithic CMOS sensor with high frame rate for FELs and synchrotrons. This particular imager, termed PERCIVAL, is specified to have more than 10 megapixels with less than 30 µm pixel size. Through the low noise performance it shall be able to detect individual 250 eV photons and accumulate up to 10^5 of them per image in a single pixel.

This activity will result in a CMOS-sensor system that may be evaluated also for proton radiography at FAIR, and at the same time provide the technological advances for tracking applications where radiation length and frame-rate are key. This joint effort will allow a technology that is typically associated with enormous non-recurring engineering costs to be explored and exploited in a much broader portfolio of applications

3.2.3.3 Timelines of Activities and expected Results

Years	Activity / Milestone	Participants
2015 – 2017	Establishment of Helmholtz-Cube as a modular development platform for high-resolution pixel detector systems in photon science and beyond	DESY, GSI, KIT
2015 – 2019	Design and construction of highly integrated gaseous detector systems	DESY, GSI, HZDR
2015 – 2019	Development and characterization of digital SiPM detector systems	DESY, HZDR, Partner: MPG HLL
2015 – 2017	Development of multi-channel bolometric detector systems	KIT
2015 – 2019	Development of pixelated diamond detectors	DESY, GSI, HI JENA, KIT

2015 – 2017	Development of a fast, large-area, back-thinned CMOS imager	DESY, GSI

3.2.4 Detector Technology and Society

Detector instrumentation is relevant also to other Research Fields of the Helmholtz Association and indeed to society at large. DTS initiated the activity “Detector Technology and Society” dedicated to networking, outreach and applications beyond “Matter” in order to

(i) raise the visibility of the topic “Detector technologies and systems” beyond “Matter”
(ii) identify applications of detector instrumentation of high societal relevance and further knowledge exchange and
(iii) seek, educate, recruit and promote young talent in the field of detector instrumentation.

To this end a number of measures, some specific to DTS, will be undertaken. General measures related to “Talent Management” are described elsewhere (Section 2.3.3).

3.2.4.1 Topical and interdisciplinary workshops

For promoting the exchange of knowledge inside and outside of the Helmholtz Association, the “Detector Technologies and Systems Platform” started to organise topical and interdisciplinary workshops. Examples are the Wilhelm und Else Heraeus Seminar on “Development of High-Resolution Pixel Detectors and their Use in Science and Society” and a topical workshop on “Tomography, data processing and image reconstruction for medicine and engineering”. Further meetings covered specific topics within DTS. In PoF-III the successful topical workshops will be continued. High-impact events like the Heraeus seminars will take place regularly. To gain further visibility satellite workshops at subject-specific international conferences like IEEE NSS/MIC will be organised. Cross topic workshops are planned together with “Accelerator Research and Development”, cross programme workshops with the cross programme activity “Data Management at Large Scale Facilities”. All workshops are open to our international partners, universities and industry.

3.2.4.2 Collaboration meetings and PhD student retreats

Community building and exchange between centres and partners is essential for the success of DTS. The annual topic meetings will inform about latest technology developments and experiences with the prototype systems. The collaboration meetings will be complemented by annual two-day meetings of the PhD students working in DTS held at one of the participating Helmholtz centres. The meetings will comprise tours through relevant facilities, talks and poster presentations of the PhD students on their current work. PhD students will meet each other in person, become familiar with related research topics and visit the collaborating centres. Furthermore, the workshops are a welcome training to present their work.

3.2.4.3 Student training and exchange

A number of centres and consortia offer regular summer schools and block courses for graduate and PhD students on detector related subjects. Examples are the DESY Summer Student Programme, the KIT DFG graduate school KSETA and the activities of MUTLink. DTS scientists are already involved in these schools. Participation of students from other centres will be encouraged and enabled.

For an intensified training DTS offers their PhD students the opportunity to spend between four and eight weeks at another Helmholtz centre. At the beginning of their PhD studies this serves to acquire special techniques needed for their future work e.g. circuit design, board assembly, FPGA programming and software design. Close to graduation students are encouraged to broaden their perspective and to get in touch with potential groups for a first post-doctoral position.

3.2.4.4 Applications of high societal relevance

Detector technology has the potential to contribute to solving the grand challenges facing society. Prominent examples of technology transfer from “Matter” into “Health” or other research fields are listed below. DTS will complement the activities of the individual Helmholtz centre technology transfer offices by systematic surveys of highly relevant and promising systems. We expect to identify a number of further worthwhile applications in PoF-III when key technologies of DTS become mature.

In-vivo dose monitoring: Proton and ion beams enable new cancer treatment options beyond conventional radiation therapy. In contrast to gamma rays or electrons, the energy of protons and ions is predominantly deposited at the end of their range. This allows a high dose to be concentrated within the tumour while sparing healthy tissue, provided that the particle range is well under control. Therefore, verification of the range of particle beams in-patient is a key factor for enabling the full potential of charged hadron therapy. HZDR and its university partners are exploiting cutting-edge detector technologies to assemble a prompt gamma imaging system for clinical use.

Detectors for Positron Emission Tomography (PET): PET is a well-established method in nuclear medicine and engineering. At the same time it is also applied to niches like dose monitoring in hadron therapy, position resolved positron annihilation spectroscopy and monitoring of reactive transport processes in heterogeneous geological material by means of radiotracers. All these applications require detectors with good energy-, position- and timing resolution. This includes the development of SiPMs in close contact to industry and fast data reconstruction using highly parallel hardware.

A particular project, co-funded by the European Commission is **ENDOTOFPET-US.** The systems consist of an endoscopic TOF-PET system with an integrated ultrasonic probe. Building such a detector system became possible only recently due to the progress in miniaturisation of components like employing SiPMs. High photon detection efficiency and efficient coincidence discrimination due to the good time resolution of SiPMs leads to improved sensitivity. This may reduce the strain for the patient by lowering both the radioactive dose and the examination time.

Positron annihilation lifetime spectroscopy for materials research: The understanding of the nature and the formation of defects is one of the key issues for the development of new and application-tailored materials in various areas. Some selected examples are ultra-fast semiconductor circuits, highly strain-resistive alloys, intermetallic clathrates, gas separation membranes and devices with interface magnetism. Positron annihilation lifetime measurements combined with annihilation spectroscopy offer a unique tool for those defect studies. The development of ultra-high timing resolution detectors based on SiPM in the scope of DTS will have a significant impact on the experimental conditions and the related research in this field. With highly efficient timing and spectroscopic resolution new areas of research will become available.

Hadron radiography and tomography: Using hadron computer tomography for hadron therapy planning will enable to calculate the critical hadron range with a significantly enhanced accuracy. To this goal both tracker and absorber modules need to be developed. Ionisation chambers and CMOS detectors are favourable devices to be applied as trackers, whereas for absorber scintillators with SiPM readout can be used. Again success is highly dependent on the development of efficient SiPMs in DTS.

Development of dose-free imaging for mammography: The “Ultrasound Computer Tomograph (USCT)” project at KIT develops a unique system for early detection of breast cancer. The system combines custom ultrasonic transducers, custom DAQ electronics, sophisticated data processing and algorithms for fast reconstruction of large data sets. The system is currently being evaluated in a clinical study. The USCT project is computationally demanding and benefits from by the parallel processing activity in DTS.