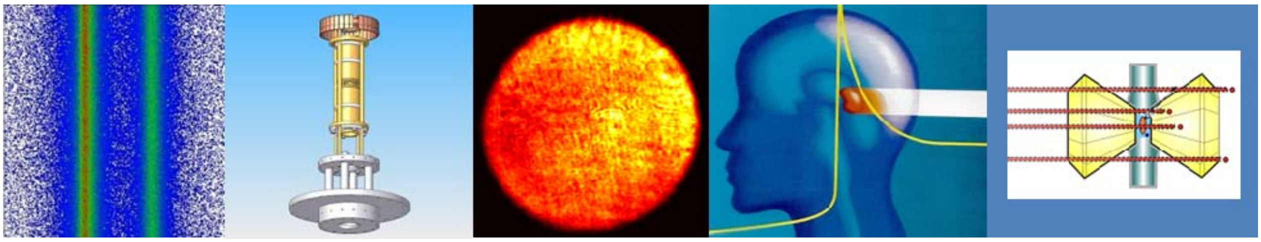
FAIR - Facility for Antiprotons and Ion Research

The Modularized Start Version



Atomic and plasma physics, and applied sciences in bio, medical and material sciences (APPA) research pillar

Science case

Darmstadt, November 12, 2012
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List of abbreviations

APPA - Atomic and Plasma Physics, and Applied sciences in bio, medical and material sciences

BIOMAT– Biophysics and Material sciences research collaboration

CDR – Conceptual Design Report

EOS - Equation of State

FAIR – Facility for Antiproton and Ion Research

FLAIR – Facility for Low-energy Antiproton and Ion Research

HED – High Energy Density

HEDgeHOB - High Energy Density Matter Generated by Intense Heavy Ion Beams

HEPM - High Energy Proton Microscopy

HESR – High Energy Storage Ring

HHT – High-Temperature plasma physics experimental area at GSI

HIHEX - Heavy Ion Heating and Expansion

HITRAP- Heavy Ions Trap decelerator at GSI

ISC – International Steering Committee

ISCEG - International Space Exploration Coordination Group

LAPLAS - Laboratory Planetary Sciences

MSV – Modularized Start Version

PAC – Program Advisory Committee

PaNTERA - Proton Therapy and Radiography

PHELIX- Petawatt High Energy Laser for Ion Experiments at GSI

PRIOR - Proton Microscope for FAIR

QED – Quantum Electrodynamics

SIS18 –The GSI Heavy Ion Synchrotron

SPARC – Stored Particle Atomic Physics Research Collaboration

TDR – Technical Design Report

UNILAC – Universal Linear Accelerator at GSI

WDM - Warm Dense Matter

XANEX- x-ray absorption near edge spectroscopy

INTRODUCTION

Atomic and plasma physics, and applied sciences in bio, medical and material sciences (APPA) is an umbrella organization, consisting of 5 independent research collaborations. It represents one of the four FAIR research pillars and comprises three research communities: atomic physics (SPARC, FLAIR), biophysics and material science (BIOMAT), and plasma physics (HEDgeHOB, WDM).

The **different research fields of the APPA collaborations** focus on the following topics:

- Atomic physics studies with beams of highly-charged heavy ions and antimatter (antiprotons) will address quantum electrodynamics in extremely strong fields, matter-antimatter symmetries, correlated many-body dynamics via ultra-short, super-intense field pulses, novel electromagnetic processes, properties of stable and unstable nuclei and tests of fundamental theories besides QED. These scientific goals request the implementation of new instrumentation able to handle the extremely broad energy and intensity ranges of the ion beams provided by FAIR as well as the special environment provided by storage rings and ion traps. The topics related to the atomic physics with highly charged ions are pursued by the Stored Particle Atomic Physics Research Collaboration (SPARC) while the FLAIR Collaboration (Facility for Low-Energy Antiproton and Ion Research) will direct its efforts towards the atomic and nuclear physics studies with low-energy antiprotons.
- Physics of dense plasmas with highly compressed heavy-ion beam bunches in combination with a high-power laser will concentrate on studies of the phase diagram in the regime of strongly coupled plasma and phase transitions in warm dense matter. The efficient generation of these states in macroscopic amounts will be boosted by the implementation of new, efficient time and space resolved diagnostics methods based on high-energy proton microscopy and intense lasers. Around these topics, two plasma physics collaborations were built: the High Energy Density Matter Generate with Intense Heavy Ion Beams (HEDgeHOB) and the Warm Dense Matter (WDM)
- Applied research benefits from the large range of beam energies and intensities for various activities, in particular in biophysics and material science. The biophysics research has two main topics: space radiation effects on humans (astronauts) and spacecraft instrumentation (microelectronics); and particle therapy using high-energy protons and heavy ions for cancer and noncancer diseases. Research in material science is dedicated to heavy-ion induced modifications in solids under extreme conditions such as short ion pulses, high fluences, and the simultaneous application of pressure and temperature. A multipurpose irradiation facility, able to uniformly scan large targets and equipped with various instrumentations for in-situ and on-line monitoring, has been designed. This facility will be built and exploited by the BIOMAT collaboration consisting of international collaborations on heavy-ion biophysics (BIO) and material science (MAT).

The APPA research program fully exploits the diverse possibilities of the full FAIR facility. Figure 1 shows schematically the distribution of the different APPA experimental areas over the FAIR site as it was initially foreseen for the complete project
The complexity and the dimensions of the project requested a strategic approach of the FAIR realization in a staged (modularized) mode, as it was defined by the FAIR Green Paper [1] in October 2009. Originally structured in two phases, the realization was restructured in six modules. Based on elaborate cost estimation and funding pledges of the FAIR member states, the first construction phase was tailored to comprise four out of the six defined

modules. This workable approach, endorsed by the International Steering Committee, changed the realization time line for the APPA relevant facilities. Especially, the delay in the realization of the New Experimental Storage Ring (NESR) confronted the SPARC and FLAIR collaborations with a new, challenging situation: a large part of the SPARC research program and the whole FLAIR program have been postponed until the realization of the fifth FAIR module (NESR Storage ring for NUSTAR and APPA, building for the antimatter program FLAIR).

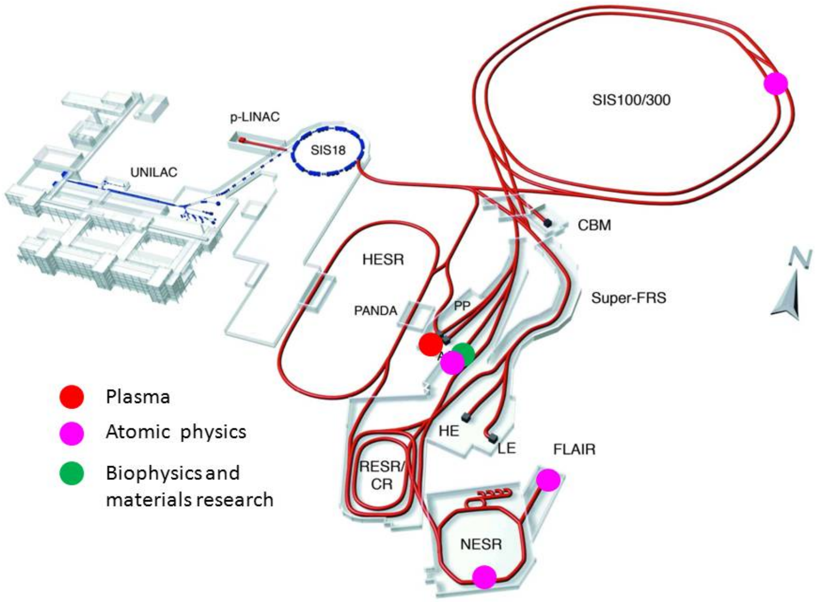

Figure 1: *Layout of the FAIR facility, full version. The colored points (see legend) indicate the various experimental areas belonging to the different APPA programs.*

At the same time, the HEDgeHOB and WDM collaborations will have to share a single beam line for their experiments (fig. 2) and the proton beam line from the SIS18 for high energy proton microcopy (HEPM diagnostics) (fig. 1) was postponed for a later stage. However, the modularized start version pulled forward the realization of the high energy AP cave, designed to accommodate the BIOMAT collaborations and part of the atomic physics program with high energy ion beams. Further optimization, triggered by the vicinity of locations and similar beam parameters lead to the realization of the so called APPA cave (fig. 2) where all APPA collaborations, excepting FLAIR, have the possibility to perform their research using heavy ion beams delivered by the SIS18 and SIS100. Especially the BIOMAT programs will take full advantage of the new irradiation station at an earlier date that originally thought.

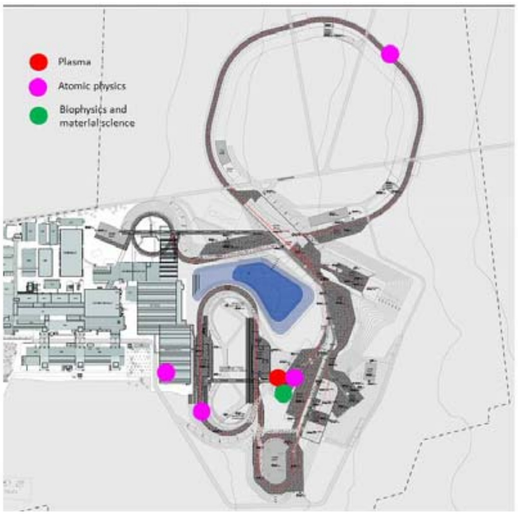

Figure .2: *Layout of FAIR facility to be realized in the modularized start version (modules 0 to 3). Different experimental areas for the APPA collaborations are marked with colored points (see legend).*

In the following, the main research topics of the APPA collaborations accessible in the FAIR start version will be reviewed pointing to the uniqueness of the FAIR experiments and with particular emphasis on the latest developments related to the physics programs and to the experimental facilities. Moreover, a perspective view beyond the FAIR MSV, for all APPA research fields, will be shortly presented.

References

[1] FAIR Green Paper: The Modularized Start Version, http://www.fair-center.de/fileadmin/fair/publications_FAIR/FAIR_GreenPaper_2009.pdf

Atomic Physics: The SPARC and the FLAIR collaborations

The scientific program concentrates on two central research areas: the physics of strong, ultra-short electromagnetic fields including the fundamental interactions between electrons and heavy nuclei (SPARC: more than 300 members from 20 countries) and the physics of antimatter explored in high-precision experiments using antiprotons in the low-energy domain (FLAIR: more than 100 members from 16 countries). Various working groups were formed for the development and construction of the projects. Prototype detectors, spectrometers, and read-out electronics are been developed and tested at different beam facilities. In particular, since the proclamation of the MSV, SPARC has worked out realization schemes for heavy ion experiments in the HESR, as well as for the installation of the CRYRING at the ESR. Both facilities will provide worldwide unique physics opportunities and will be essential in the anticipated program of SPARC already for the time of the MSV. The installation of CRYRING, dedicated Low-energy Storage Ring (LSR) for FLAIR, may even enable a much earlier realization of the physics program of FLAIR with slow anti-protons.

SPARC: Atomic physics, quantum electrodynamics, ultra-high electro-magnetic fields studies with beams of highly-charged heavy ions

The international FAIR project is promising the highest intensities for relativistic beams of stable and unstable heavy nuclei, combined with the strongest available electromagnetic fields, for a broad range of experiments. This will allow the extension of atomic-physics research across virtually the full range of atomic matter, i.e. concerning the accessible ionic charge states as well as beam energies. In SPARC experiments in two major research areas are planed: collision dynamics in strong electro-magnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use the relativistic heavy ions for a wide range of collision studies. In the extremely short, relativistically enhanced field pulses, the critical field limit (Schwinger limit) for lepton-pair production can be surpassed by orders of magnitudes and breakdowns of perturbative approximations for pair production are expected. The detection methods of reaction microscopes will give the momentum of all fragments when atoms or molecules are disintegrating in strong field pulses of the ions. This allows exploring regimes of multi-photon processes that are still far from being reached with high-power lasers. In particular, the storage ring HESR will be exploited for collision studies. Here, fundamental atomic processes can be investigated for cooled heavy-ions at well-defined charge states interacting with photons, electrons and atoms. These studies can even be extended at the CRYRING at ESR to the low-energy regime where the atomic interactions are dominated by strong perturbations and quasi-molecular effects.

The other class of experiments will focus on structure studies of selected highly-charged ion species, a field that is still largely unexplored; with determinations of properties of stable and unstable nuclei by atomic physics techniques on the one hand, and precision tests of quantum electrodynamics (QED) and fundamental interactions in extremely strong electromagnetic fields on the other hand. Different complementary approaches such as relativistic Doppler boosts of optical or X-UV laser photons to the X-ray regime, coherent radiation by channeling of relativistic ions, electron-ion recombination, and electron and photon spectroscopy will be used and will give hitherto unreachable accuracies. These transitions can also be used to laser-cool the relativistic heavy ions to extremely low temperature, which could lead to a break-through in accelerator technology. Another important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP. This scenario will enable high-accuracy experiments in the realm of atomic and nuclear physics, as well as highly-sensitive tests of the Standard Model.

Comparison with other experiments in the field

For highly-charged heavy ions, FAIR will be worldwide unique with respect to the beam energies and intensities. Fixed target experiments for highly-charged ions at relativistic energies with $\gamma>2$ will be available only at FAIR. In particular, the HESR will provide the possibility to exploit cooled relativistic ion beams. Moreover, the use of storage rings for highly-charged ions is by itself a unique aspect. Concerning the beam intensities, the storage rings encompasses a large dynamical range providing highest intensities for cooled ion beams but accomplishes also precision experiments with single stored ions. At lower energies, comparable to the ESR, similar beam properties in terms of energies, intensities and charge states are offered only at heavy-ion accelerator and storage ring facility Lanzhou (China). However, at Lanzhou no deceleration option for highly-charged ions as available for CRYRING and HITRAP is foreseen. To some extend CRYRING might be compared with the Heidelberg TSR storage ring which is planned to be installed at ISOLDE/CERN. However, only at CRYRING the range of available charge states extends even to the heaviest bare ions, e.g. bare uranium.

Recent Developments

The most recent developments at FAIR with respect to the atomic physics collaborations are closely related to the novel physics opportunities provided by the heavy ion storage ring experiments at the HESR and to the transfer of CRYRING to the current ESR. Whereas the high energy APPA cave offers direct SIS100 beams of highly charged heavy ions up to 10 GeV/u, HESR can store cooled beams at energies of up to a few GeV/u (not feasible at any other place in the world). The High-Energy Storage Ring (HESR), which was primarily designed for experiments with stored and cooled anti-protons [1], turned out to be a well-suited facility which can accommodate a range of SPARC experiments with high-energy stored heavy-ion beams. The HESR can store cooled beams at energies of up to a few GeV/u and can thus enable unique atomic physics experiments which are not feasible at any other place in the world. This is in particular true for the use of cooled ion beams at relativistic energies with γ–values ranging from 2 to 6, an option unambiguously documented in a recent feasibility study [2]. This feasibility study is considering electron cooling, stochastic cooling, ion optical properties at the foreseen location of the internal target as well as storage times relevant for the planned in-ring experiments (Fig. 3). Together with the specified, unrivalled properties of the HESR, the frequencies of novel laser and laser-driven sources in the visible and the x-ray regime can even be boosted in combined experiments with heavy ions. Soft x-ray lasers, as developed for experiments at ESR and NESR will now give access to the study of transitions at much higher transition energies. Especially, the interaction with highly-charged relativistic ions, novel multi-keV photon sources will access new regimes of non-linear photon matter interaction and the effects of QED in strong Coulomb fields.

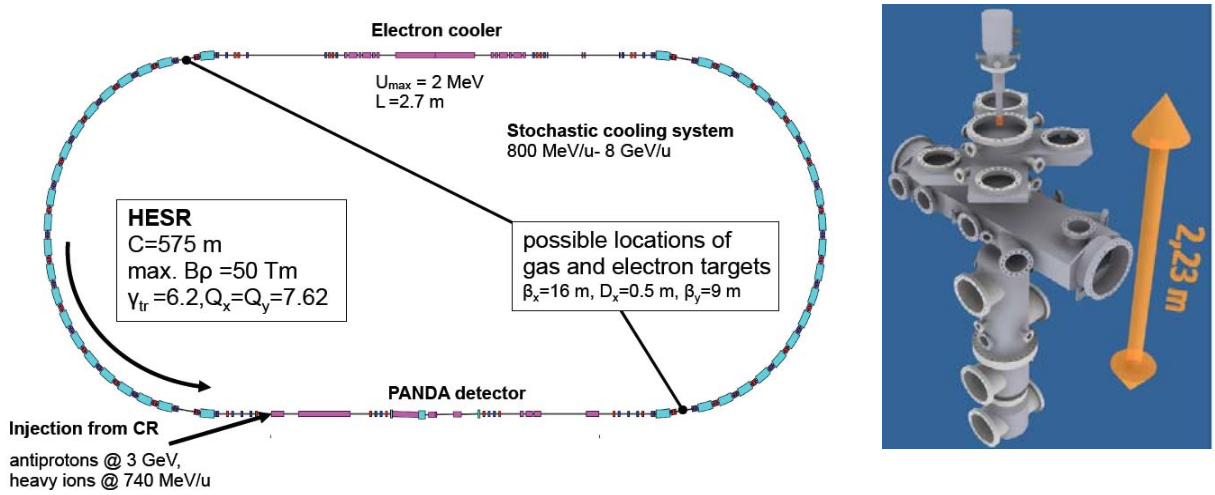

Figure 3. *Schematic view of the HESR. Main components and possible locations of the SPARC experimental setups are indicated (left). Design drawing of the internal gas target station for the SPARC experiments at HESR (right).*

Further physics topics to be addressed are: pair-production phenomena, relativistic photon-matter interaction, correlated electron motion studied by target double-ionization, test of special relativity, bound state QED and nuclear parameters, exotic nuclear decay modes in highly-charged ions, and parity non-conservation in high-Z ions and extreme electromagnetic fields.
As part of the Swedish in-kind contribution to FAIR, **CRYRING** has long been foreseen for relocation to Darmstadt, as integral instrument for the FLAIR facility [3]. In a Swedish-German joint effort, a project group has worked out a strategy for an early installation of CRYRING in the evolving GSI/FAIR accelerator complex [4]. Downstream of ESR an ideal location for setting up CRYRING was found (Fig. 4) where at minimum cost the access to beams of all ion species available at GSI is guaranteed and opens an exciting opportunity for novel research. The scientific program of CRYRING@ESR will focus on atomic and nuclear physics of exotic systems, exploiting the available unique gas jet target and electron target, bridging the gap between the beam energies at the ESR (≥ 4 MeV/u) and at HITRAP (≤ 5 keV/q). The fast ramping capability of CRYRING will give access to intense beams of bare and exotic nuclei at low energies.
Thus, atomic collisions can be studied in the adiabatic regime by recoil ion momentum spectroscopy and, in addition, the low Doppler shift/spread provides unique conditions for atomic structure investigations based on electron and photon detection.
With its independent RFQ injector beam line, CRYRING@ESR will serve as test bed for prototyping FAIR components in an operating environment.

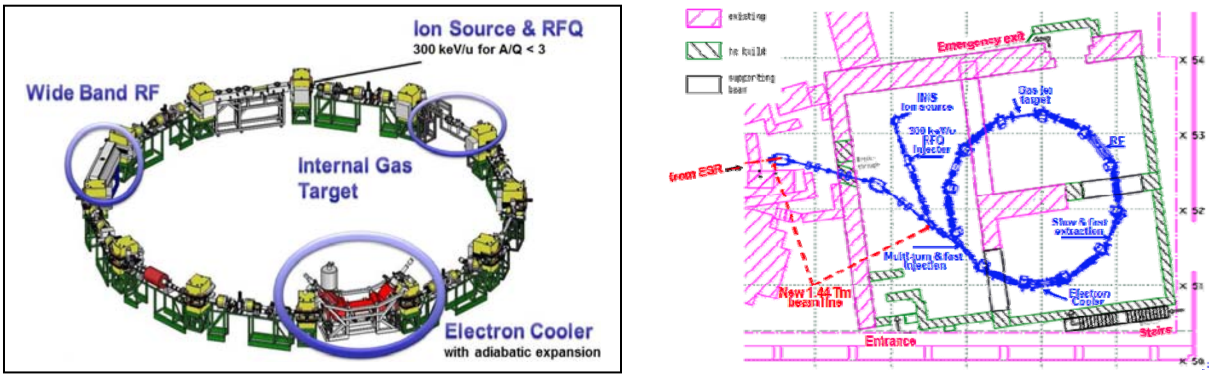

Figure 4: *CRYRING with its central experimental installations (left). Proposed location of the CRYRING at Cave B in SIS18 target hall (right).*

Progress report

The R&D activities of the SPARC collaboration at the new facility are centred on the three main experimental areas for atomic physics: APPA-Cave, HESR and CRYRING. Different task shared by the various working groups also emphasize essential precursor experiments at the present experimental storage ring ESR of GSI and other suited, external facilities and focus as well on the development of new prototype set-ups for FAIR.

- The report “CRYRING@ESR: A study group report” [4] has been evaluated and accepted as a TDR by FAIR. The transfer of CRYRING to GSI has already been completed and currently CRYRING is getting installed at the ESR within the SIS18 target hall.
- A laser cooling experiment conducted for 122 MeV/u C^{3+} ions at the ESR [5] demonstrated for the very first time cooling of a highly-charged ion down to an unsurpassed longitudinal momentum spread $\Delta p/p < 10^{-7}$ by exploration of the Doppler boost, similar as it is finally planned for the experiments at HESR and SIS100/300. In addition, at the ESR, Time Dilation in Special Relativity has been successfully tested using $^{7}Li^{+}$ at a velocity of $\beta = 0.34$, in accordance with the most stringent previous test.

TDRs for laser experiments at SIS100, HESR, and CRYRING are currently being worked on.

- As a feasibility test towards the future FAIR experiments, a new setup for high resolution x-ray spectroscopy of Li-like Uranium via resonant coherent excitation (RCE) has been installed in Cave A and has been successfully commissioned with a cooled 191.5 MeV/u U^{89+} beam from the ESR to study the $1s^2 2s$-$1s^2 p_{3/2}$ electron transition. A TDR for channeling experiments at SIS100 and HESR is under preparation.
- Newly developed position-sensitive Ge(i) and Si(Li) detectors were taken into operation (see fig.5). Detector performance tests were performed with photon beams at the ESRF, DORISIII, and PETRAIII synchrotron facilities. A TDR is being worked on.

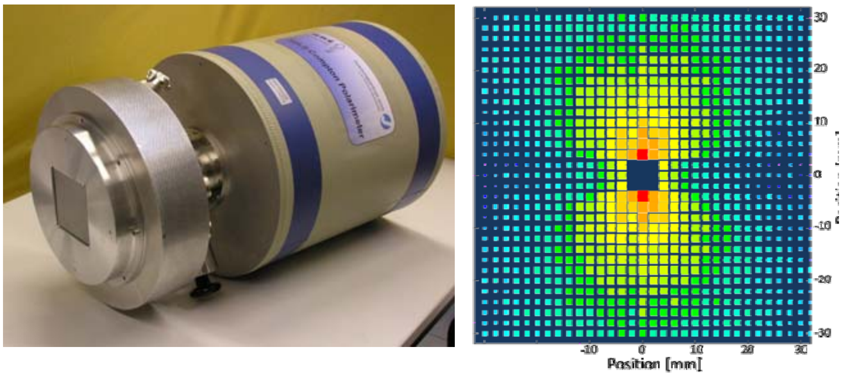

Figure 5: *Prototype Si(Li) Compton polarimeter as developed by the SPARC collaboration. The position sensitivity of this detector allows for accurate Compton polarimetry of atomic transitions at x-ray energies above 70 keV (left).*

- Extensive investigations on the production of cryogenically cooled liquid hydrogen and helium droplet beams at the experimental storage ring ESR were carried out [6] with the goal to achieve high area densities for these low-Z internal targets. The results show that an area density of up to10^{15} cm^{-2} is achieved for both light gases. Based on these systematic studies, a TDR for the internal target at HESR has been worked out and submitted.
- The design, construction and installation of a cryogenic micro-calorimeter array “maXs" dedicated for high resolution x-ray spectroscopy experiments at FAIR is progressing. maXs is based on the detection principle of metallic-magnetic calorimeters and is operated at a temperature of about 30 mK. Beside its high-resolution properties it will also provide timing capability. A TDR is ready for submission.
- A breakthrough was achieved by a very first high-resolution measurement of the Lyman-α transitions in high-Z hydrogen-like systems as a precondition for a critical test of QED in the widely unexplored domain of very strong fields. The measurements were carried out on hydrogen-like Au^{78+} at the ESR storage ring and were made possible by the development of the FOCAL x-ray crystal optics which overcomes both the limiting spectral resolving power. The present efforts are an important pilot experiment for SPARC at FAIR emphasizing the physics of extreme electromagnetic fields.
- For experimental studies concerning the electron dynamics in transiently formed superheavy quasi-molecules presently a combination of electron/recoil spectrometers is designed and built. This setup consists of a longitudinal reaction microscope for simultaneous position resolved spectroscopy of low energy electrons and recoil ions. The prototype of an imaging forward electron spectrometer has been installed and commissioned at the ESR.
- For the spectroscopy of electrons and positrons originating in collisions of very heavy, highly-charged ions with atoms/molecules/fiber targets in the relativistic domain, a concept for a reaction microscope in combination with a magnetic electron/positron spectrometer is currently been developed. A TDR will be written by the end of 2013.

- HITRAP, a linear decelerator for heavy, highly-charged ions is installed downstream ESR. The deceleration is done in two steps, by using an interdigital H-type structure and a radiofrequency quadrupole. The first part decelerates from 4 MeV/u to 500 keV/u and the second one further down to 6 keV/u. Before being distributed to the experiments, the decelerated beam is captured in a Penning trap for cooling. The facility is under commissioning and a number of online and offline tests have been recently performed.
- USR@FLAIR: At the Max-Planck-Institute for Nuclear Physics in Heidelberg the operation of the first quarter of the Cryogenic Storage Ring (CSR, see figure 6), the prototype of the Ultralow energy Storage Ring (USR) for FLAIR, was successfully demonstrated at 2 K temperature. A TDR for the USR@FLAIR is under preparation.

Figure 6: *The Cryogenic Storage Ring CSR at MPIK, the prototype for the USR at FLAIR. One quarter was already successfully operated at 2K temperature (left). A gold plated quadrupole structure (right).*

Glimpse beyond MSV

The low-energy antiproton physics community is making constant progress at the Antiproton Decelerator of CERN. Highlights in recent years were the first trapping of neutral antihydrogen atoms by the ALPHA collaboration and the first formation of antihydrogen in a cusp trap by the ASACUSA collaboration, which together were selected as the "Highlight of the year 2010" by Physics World. With ALPHA observing a first resonant hyperfine transition in trapped antihydrogen in 2011, ATRAP reporting also the trapping of antihydrogen in 2012, and ASACUSA preparing a polarized antihydrogen beam from the cusp trap, the phase of antihydrogen spectroscopy is about to start. Two experiments to measure the gravitation of antihydrogen, AEgIS and Gbar, were approved. ATRAP and a newly formed collaboration BASE are under way to measure the g-factor of the antiproton in a Penning trap. To cope with these increased activities, CERN has approved the construction of an additional storage ring called ELENA to more efficiently decelerate the antiproton beam from 5 MeV to 100 keV, and for opening the possibility of using an internal target for collision studies. A TDR is currently being prepared; the completion of ELENA is expected in 2017. These developments demonstrate the rich science case for low-energy anti-proton physics as anticipated by the FLAIR collaboration at FAIR. With CRYRING@ESR two fully commissioned storage rings would be available, and, by installing an anti-proton transfer line, the physics program of the FLAIR collaboration could be realized at a very early stage. This option was recently (in spring 2012) discussed at a FLAIR workshop at GSI. One may note that a further important facility for FLAIR, HITRAP at the ESR, is currently getting commissioned. This portfolio of facilities (CRYRING, HITRAP and the USR) will enable novel physics opportunities such as slowly extracted anti-proton beam which are even not covered by ELENA at AD.

Ultra-high power lasers combined with heavy-ion beams at FAIR represent a novel access to atomic physics and high-field physics. Building on the well-established expertise within the Helmholtz centers and Helmholtz Institute Jena, the Helmholtz Center Dresden/Rossendorf has proposed a “Helmholtz-Beamline for FAIR” which is part of the Helmholtz-Roadmap for future research infrastructures (FIS, “Forschungsinfrastrukturen”). Coupled to various experimental stations of the FAIR accelerator complex this will lead to a significant expansion of the experimental options at FAIR for the realm of atomic and plasma physics. A detailed feasibility study has to be worked out and submitted until 2016.

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Plasma Physics Research: The HEDgeHOB and the WDM collaborations

FAIR will deliver very intense, bunched and highly focused beams of all ion species up to uranium. Such beams will deposit hundreds of kJ/g specific energy in solid matter that will induce exotic states of high energy density (HED) in the material. A strong plasma physics community, organized in two collaborations, aim for using these beams for unique studies.

The HEDgeHOB collaboration, comprising about 170 scientists from 14 countries will carry out novel research into matter under extreme conditions of temperature and pressure, similar to those in the interiors of stars, brown dwarfs and giant planets. The WDM collaboration formed by 70 scientists from 8 countries will concentrate on properties of warm dense matter with an emphasis on radiative properties. For this purpose special target configurations have been worked out that allow precise measurements with a minimum of measured quantities. State of the art optical and laser diagnostics will be used to improve the atomic physics description of this special state of matter.

HEDgeHOB: Studies on High Energy Density Matter with Intense Heavy Ion and Laser Beams at FAIR

The research program envisaged at the FAIR Modularized Start Version will focus on the equation of state of different materials in so far unexplored regions of the phase diagram, the properties of compressed matter at medium temperatures, and related to these major goals, such as radiation hydrodynamics, magneto-hydrodynamics, etc. Two complementary experimental concepts are proposed by the HEDgeHOB collaboration:

1. **HIHEX** (Heavy Ion Heating and Expansion): In a HIHEX-type experiment [1], a cylindrical or plane target is heated fast compared to the hydrodynamic expansion time. By such quasi-isochoric heating, high entropy states as well as high energy density states are generated. After heating, the sample isentropically expands and passes through the regions of interest in the phase diagram. The variability of the beam focus at the target provided by a superconducting strong final focus system allows for cylindrical and plane geometries of the experiment.
2. **LAPLAS** (Laboratory Planetary Sciences): LAPLAS scenario [2] makes use of cryogenic targets like solid hydrogen and other noble gases, confined by an outer cylinder of a heavier material, such as lead or gold. The outside cylinder is heated by a beam with an annular focal spot, generated by a high-frequency beam rotator (wobbler) [3]. While the outer material is heated and subsequently expands, the inner cryogenic material is not heated, stays cold and is compressed by the expansion

process of the outer cylinder. This ensures high compression of the investigated material at low entropy.

FAIR MSV will be a very efficient tool to generate high energy-density states in macroscopic amounts in the laboratory under controlled and reproducible conditions, and to address the long-standing open questions of basic equation of state (EOS) research, allowing studies of the phase diagram in the regime of strongly coupled plasma and warm dense matter where phase transitions are expected to occur (Fig. 7). Since the perpendicular proton beam line from the SIS-18 synchrotron for the high energy proton microscopy (HEPM) diagnostics will not yet be available for the FAIR MSV experiments, the HEDgeHOB collaboration proposes a new experiment:

3. **PRIOR** (Proton Microscope for FAIR). The worldwide unique HEPM facility PRIOR [4] which is currently being assembled at a SIS-18 beam line of GSI will be integrated into the SIS-100 HEDgeHOB beam line at FAIR. This will allow employing high energy (5–10 GeV), high intensity ($5 \cdot 10^{12}$ per pulse) proton beams for fascinating multidisciplinary research already during the MSV phase of FAIR, jointly with the BIOMAT collaboration. In particular, experiments on fundamental properties of materials in extreme dynamic environments generated by external drivers (e.g., a pulsed power driver or shock wave generators) prominent for materials research and non-ideal plasma physics as well as the PaNTERA (Proton therapy and radiography) experiment, with a great relevance to biophysics and medicine, will take full advantage ofthese beams.

Comparison with other experiments in the field

The most significant information so far has been obtained using shock wave methods. Due to the shock, material is compressed and irreversibly heated, leading to high values of pressure and entropy. Chemical explosions, light-gas guns, high current Z-pinches, high power lasers and in a few cases even nuclear explosions were used to expose matter to high pressure up to the Gbar regime. However, using the shock wave compression method, only a narrow region of the principal and porous Hugoniots have been investigated (see Fig. 7) and for most of the metals, the available information is limited to the knowledge of the Hugoniots and model estimations of the critical point. As soon as we will be able to investigate high energy density samples under reproducible conditions in the laboratory with high repetition rate, we can expect a rapid progress in this field.

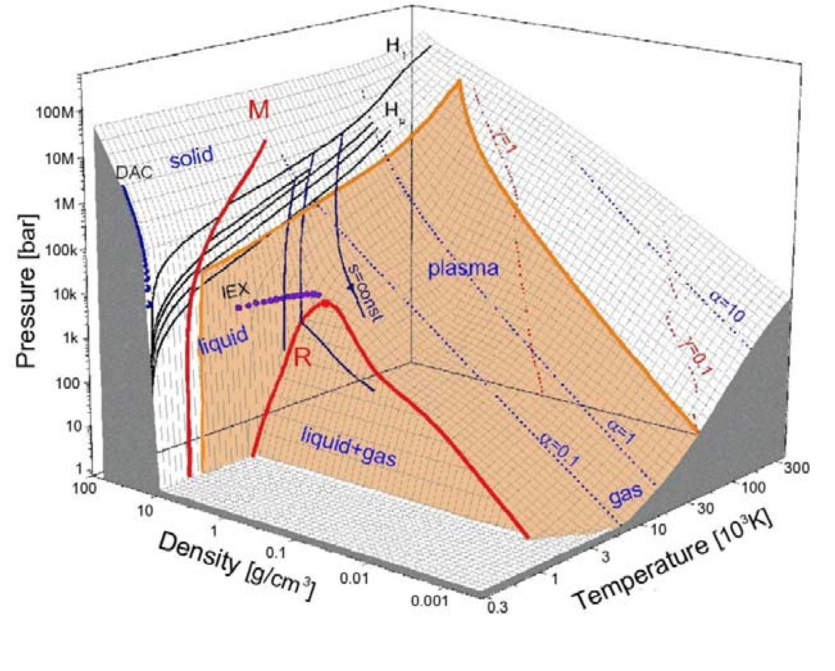

Figure 7: Equation-of-state surface for lead in pressure-density-temperature variables. The painted area bounded by corresponding isochore and isentrope shows the parameter region accessible in the HIHEX experiment. Also shown: M – melting region, H – principal and porous Hugoniots, DAC – diamond-anvil-cell data, IEX – isobaric expansion (“exploding wires”) data, S – release isentropes, R – boundary of two-phase liquid-gas region with the critical point, isolines of

	ionization degree α and plasma non-ideality parameter γ.

Intense heavy ion beams open a new pathway to address this research field experimentally. The particle beams deposit their energy over extended volumes of matter and are thus capable of inducing these exotic states in the target material directly, without generation of shocks. The main advantages of using intense ion beams include high repetition rate of the driver, high beam–target coupling efficiency and rather large samples of HED matter with fairly uniform physical conditions (no sharp gradients).

Already today GSI accelerators deliver the most intense heavy ion beam for plasma physics experiments. The beam parameters of the FAIR facility outnumber the current status in many respects: it is not only the absolute number of particles per bunch that will increase by about 3 orders of magnitude, but also the beam power will increase by a factor of 3000 due to pulse compression down to 50 – 70 ns. The specific energy deposition will increase from 1 kJ/g, which is a typical value for current experiments, to about 600 kJ/g. This opens the possibility to reach out into currently inaccessible parameter regimes for HED / WDM states of matter (see Fig. 7).

Progress report

Extensive experimental and theoretical work has been carried out over the past few years to assess the potential of intense heavy ion beams to the HED physics research at FAIR. At the "High-Temperature" (HHT) area of GSI, a comprehensive experimental setup for HED experiments has been developed and built up. The main aims of the experiments performed at the HHT area were commissioning of recently developed diagnostic instruments and methods for the HEDgeHOB experiments at FAIR; tests of different beam-target configurations for EOS studies; optimization of transport, focusing and diagnostics of intense heavy ion beams; obtaining new data on thermo-physical properties and hydrodynamic response of various materials in HED states near boiling curve, two-phase liquid-gas and the critical point regions [5]. In particular, HED properties of lead, tin, copper, aluminum, tungsten, tantalum, and sapphire have been studied using the "plane-HIHEX" design concept.

Recently an international project was started within the HEDgeHOB collaboration for the development of a new proton microscopy facility called PRIOR (Proton Microscope for FAIR). PRIOR will provide a significant step forward in both spatial and temporal resolution. Its installation at GSI and commissioning in dynamic experiments with the 4.5 GeV proton beam from the SIS-18 synchrotron is planned for 2013 / 2014. This worldwide unique proton microscope facility will provide at GSI and later – at FAIR a capability for unparalleled high-precision experiments in plasma physics, high energy density physics, materials research and biophysics.

In the PHELIX laser bay and the Unilac experimental cave Z6 the focus of the FAIR related activities was laying on the development of laser based plasma diagnostics. Successful X-ray backlighting was demonstrated by imaging a thin wire, heated with PHELIX generated hot electrons, and recorded by Co K-α X-rays. Together with the collaborators of the TU Darmstadt first X-ray Thomson scattering experiments on high pressure and high density matter have been performed successfully. Hereby liquid carbon was generated with laser driven shock compression and analyzed by scattering Ti He-α X-rays.

A substantial work has recently been done by the collaboration in order to prepare the Technical Design Reports (TDR) for the key components of the HEDgeHOB experimental installation. In particular, draft TDRs have been worked out for the superconducting Final Focus System (IHEP-Protvino, Russia), LAPLAS high-frequency beam rotator (wobbler) system (ITEP-Moscow, Russia) and the LAPLAS cryogenic target preparation and delivery system (LPI-Moscow, Russia).

Glimpse beyond MSV

The investigation of dense plasmas is a challenging task, because most of the standard diagnostic tools, which are well known from atomic and plasma physics, fail at the high density and complex electronic properties of the plasma samples to be probed. Furthermore, these extreme states of matter are available in the laboratory only in a highly transient state. The HIHEX and LAPLAS experiments planned by the HEDgeHOB collaboration therefore require a high temporal and spatial resolution of the diagnostics, comparable with the hydrodynamic time scale for the expansion of the beam-heated target material.

The full version of FAIR will allow for the following components, essential for advancing the HEDgeHOB experiments in the future:

- The beam-line from SIS18 perpendicular to the SIS100 beam line for the HEPM diagnostics with the PRIOR facility. Proton Microscopy with a 4.5 GeV proton beam delivered from SIS-18 simultaneously with the plasma-generating intense beam from SIS-100 is an extremely attractive future for the HEDgeHOB experiments, ensuring significant progress in HED physics research due to precise investigations on the density evolution of the plasma samples. Determination of the target density distribution is a great challenge for both HIHEX and LAPLAS experiments: the expected target areal density is up to 20 g/cm^2 (Pb, Au, etc.) whereas the density distribution has to be measured with rather high spatial (10 µm) and temporal (10 ns) resolution with the density reconstruction accuracy at sub-percent level. This problem can be uniquely solved by the HEPM technique.
- The High-energy Petawatt (HEPW) laser. The PHELIX laser project (Petawatt High Energy Laser for Ion Experiments) at GSI provides photon pulses of the kiloJoule total energy with a peak power up to one Petawatt. Having such a HEPW laser beam available at FAIR will allow both LAPLAS and HIHEX experiments to greatly benefit by using diagnostic tools such as X-ray Thomson scattering and X-ray backlighting to characterize the states which have been achieved. Moreover, the combination of high power laser and intense ion and proton beams is unique and will enable new experimental techniques. For example, the laser beam is able to deposit an additional amount of energy during the ion-beam heating either via direct irradiation or by energy deposition of laser-produced particle beams, and thus to induce a strong shock wave directly in extreme states of matter. This will open a pathway to address the equation of state physics of giant planets, which otherwise is only possible during rare events like large meteor impacts.

WDM: Radiative Properties of Warm Dense Matter Produced by Intense Heavy Ion Beams

The technical proposal of the WDM collaboration describes in detail the use of isochoric ion beam heating by dynamic confinement. While this concept is still considered as an important experimental approach to study warm dense matter it was optimized for diagnostics by x-ray scattering. Since the availability of a high power PW-laser for this diagnostics is not guaranteed within the Modularized Start Version of FAIR, additional target schemes have been developed and will be exploited at FAIR by the WDM collaboration:

- **Dynamic Confinement** in cylindrical geometry uses a low-Z tamper that is transparent for x-ray diagnostics. Due to the isochoric heating the density of the target, ρ_0 remains constant and the energy deposited by the ion beam is equal to the internal energy ε of the heated matter implying that any measured quantity is a function of a well-defined thermodynamic state (ρ_0, ε). This schema has been further developed to spherical symmetry [6] and related X-ray scattering diagnostics.
- For absorption and emission measurements in WDM thin targets with a constant temperature are prerequisite. For this purpose a scheme of **isothermal expansion** has been worked out [7] and is under development for spectrally resolved opacity measurements in high-Z target foils. Absorption measurements in the X-UV range are sensitive to the matter temperature down to a few eV.

- To determine basic properties of matter in the two phase region and to determine the location of the critical point which has still a large uncertainty for many substances with high boiling temperature, the scheme of **quasi-static heating** has been proposed [8]. Thin target foils are required for the measurement. Since the foil is heated homogeneously at constant pressure the measurement of the surface temperature is sufficient to determine the heat capacity c_p. A measurement of the surface expansion directly determines the caloric expansion coefficient. The sensitivity of the measurement can be increased significantly if a stack of equally spaced target foils is heated and the moment of gap closure is detected by monitoring the surface velocity of the outer foils.

In addition to the new target configurations two new developments in optical diagnostics have been adopted:

- **X-ray absorption near edge spectroscopy (XANES)** is capable to determine temperatures in the few eV range down to 0.1 eV and is therefore well suited to the startup phase of FAIR. As has been demonstrated recently [9] high quality XANES measurements can already be performed with a rather moderate laser system: 5 J energy, 1.4 ps duration, 0.53 mm wavelength beam focused on an Er target being optimized in the range of 1.50 keV to 1.75 keV (Al-K-edge).
- **Polycapillary X-ray lenses** allow enhancement factors of up to 3000 over traditional experiments that had low photon conversion due to 4π dilution [10]. Therefore, table top 100 mJ femtosecond lasers that allow creating small bandwidth K-alpha radiation, up to the 20 keV range, might be suitable for X-ray diffraction measurements. We envisage implementation of these low energy laser systems for advanced diagnostics in the eV temperature range.

Comparison with other experiments in the field

In recent years XUV/X-ray Free Electron Lasers (XUV: FLASH in Germany, XFEL: LCLS in USA, SACLA in Japan) have gained an important role in the investigation of warm dense matter. Due to the fs-laser irradiation, exotic states of matter are created in a short time period [11]. Effective photoionization of inner-shells transforms almost instantaneously the solid into a *hollow crystal*. The hollow crystal carries a huge potential energy that is released via a burst of high-energy Auger electrons. In the following, conduction band electrons are heated up to tens of eV initiating disintegration of crystalline order via electron-phonon coupling on ps time scale [11]. The XUV/X-ray FEL related investigations are highly transient and pass via exotic states of matter. Due to efficient Auger electron heating it looks difficult to access matter in the eV temperature range.
Therefore, intense heavy ion beams that create homogenous, almost static (on atomic time scale) samples in the eV temperature range are not only complementary but highly advantageous for the investigation of Warm Dense Matter properties by itself.

Progress report

Sophisticated numerical tools are necessary to develop and optimize target configurations and diagnostic techniques. For this purpose the 2D-Radiation Hydrodynamics code RALEPH-2D was developed by the WDM-Collaboration [12]. The code is supplemented by the new Equation of State model FEOS [13]. For the treatment of matter in the two-phase region a new hydrodynamic approach was developed that allows the description of matter passing through metastable states in the liquid-vapor region [13].
The new developed numerical tools have been used to elaborate experimental set-ups to use the target concepts of isothermal expansion and quasistatic heating at FAIR. A set-up to measure frequency resolved opacities based on isothermal expansion has been implemented and tested at the HHT experimental area in several runs [14]. Backlighters, spectrometers, and detectors in the experimentally challenging XUV wavelength range are under development. Techniques for background suppression have been worked out. Methods to avoid target contaminations and to reduce experimental errors are currently

studied. The TDR for the plasma physics target chamber in the APPA cave is under preparation by the WDM collaboration.

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Biophysics and Materials Research: The BIOMAT collaboration

The future beams are of great interest for biophysics and material science. The FAIR user facility for applied sciences will be worldwide unique and will allow the communities to investigate effects induced when relativistic ions deposit large amount of energy within nanometric length and short time scales. In biophysics, relativistic charged particles will be used to assess the molecular mechanisms of radiation action in living system, with main applications in space radiation protection and cancer therapy. For materials research the interest of high-energy, high-intensity particle beams is two-fold: (1) The observation of short time processes and modifications triggered in bulk material using the information provided by particles and photons emitted from the surface. (2) The investigation of materials response under multiple extreme conditions. Compared to pressure and irradiation applied separately, effects on structural behaviour are significantly different when relativistic, heavy ion irradiations are performed under high pressure. The combination of pressure with the deposition of large energy densities by ion beams yields new dense metastable high-pressure phases. This approach offers exceptional opportunities, including a new strategy for the recovery of high-pressure structures that are otherwise inaccessible.

Biophysics

The FAIR accelerator complex at GSI will be a unique facility, where radiobiology of heavy ions with energies up to about 10 GeV/u will be for the first time explored. During the past reporting period, substantial advances have been made by the Biophysics collaboration toward the construction of the experimental setups for the future experiments in the APPA cave. Preliminary tests have been performed at the SIS18 and in the external partner accelerator facilities members of the APPA collaboration: Brookhaven National Laboratory (NY, USA), Los Alamos National Laboratory (NM, USA), HIT (Heidelberg, Germany), ITEP (Moscow, Russia) and HIMAC (Chiba, Japan). We have *a)* built and tested a new experimental setup for measurements of the shielding properties (including dose attenuation, neutron production, and microdosimetry spectra) of different materials and *b)* demonstrated the potential use of relativistic protons in theranostics.

Space radiation

The International Space Exploration Coordination Group (ISCEG) is a consortium of the 14 main National Space Agencies (including NASA, ESA and DLR) to coordinate the International efforts in the exploration of the Solar System. The ISCEG roadmap clearly commits the Space Agencies to exploration, and identifies cosmic radiation as the major health hazard in this grand challenge [1]. In fact, galactic cosmic radiation (GCR) is very penetrating, with energy spectrum peaking around 1 GeV/u and extending far beyond, in energy regions that have never been experienced by humans and not even tested in the laboratory. The paucity of biological data on the effectiveness of GCR particles is cause of large uncertainties (>400%) in the risk estimates for long term missions, with excess lifetime cancer risk estimates that can exceed 15% for a Mars swingby [2].

To reduce uncertainties and develop appropriate countermeasures, more research on the biological effects of space radiation is needed. These studies should be based at accelerators and are indeed supported by NASA (Space Radiation Health Program – SRHP) at the Brookhaven National Laboratory and by ESA (Investigation on Biological Effects of radiation – IBER) at GSI [3]. FAIR offers a number of unique opportunities in this frame. In particular, the use of very high energy and very heavy ions makes possible realistic tests of shielding materials to be used in space [2]. With the support of ESA, we have now built and tested an experimental setup for measurements of the shielding properties of different materials, including Mars regolith, moon regolith (Fig. 8), and new hydrogen-rich materials produced by different companies (Cella Energy, Thales Alenia Space) [4].
The experimental setup consists of several instruments (motorized double-wedge target, gas ionization chamber, BaF-telescope, scintillators, tissue equivalent proportional chamber) for a fast and standardized evaluation of the shielding properties in terms of dose attenuation (Bragg curve), neutron production, and microdosimetric spectra (quality factor of the transmitted field).

Figure 8: *Dr. Chiara La Tessa, head of the Radiation Physics Group in the Biophysics Department, prepares a Mars regolith target for measurements of the shielding properties in Cave A at GSI (experiment supported by ESA). Photo by Gabi Otto, press release in* http://www.gsi.de/de/start/aktuelles/detailseite/datum////schutz-fuer-menschen-auf-dem-mars.htm

The same setup mounted for the ESA experiments has been used for the first tests of the FAIR cave shielding materials in collaboration with the GSI Radiation Safety Department (Dr. Georg Fehrenbacher et al.). First tests include graphite and soil targets. These measurements will be used to benchmark the Monte Carlo code calculations used by the Radiation Safety to design the shielding of the FAIR caves and the beam dumps.

Medical applications

GSI led the first European pilot project in heavy ion therapy (1997-2008). Patients are now treated in Heidelberg at the HIT facility built by GSI. BIOMAT at FAIR will be used as a test bed for novel applications in particle therapy. In particular, in collaboration with the PRIOR experiment in Plasma Physics (see section Plasma Physics in this document), we have patented a system for image-guided stereotactic radiosurgery using relativistic protons (Fig.

9). With this system, a very high energy (4.5 GeV) proton beam will be directed on the patient from different angles [5]. The cancer or noncancer (e.g. brain aneurysm) lesion will be treated in the plateau region of the Bragg curve, but the very low lateral scattering and the possibility to detect the transmitted beam open new, unprecedented scenarios in theranostics. In fact, the magnetic focusing PRIOR setup can reach a spatial resolution around 10 μm, and the imaging can be produced online, thus allowing precise tracking of the target, reduction of the margins, increase of the dose, and consequently improved medical outcome. After the first biological images obtained at the ITEP accelerator in Moscow [6] we have recently got the first high-energy proton tomography images at the 800 MeV proton beam accelerator at the Los Alamos National Laboratory, using both a mouse and an anthropomorphic phantom (Fig. 10).

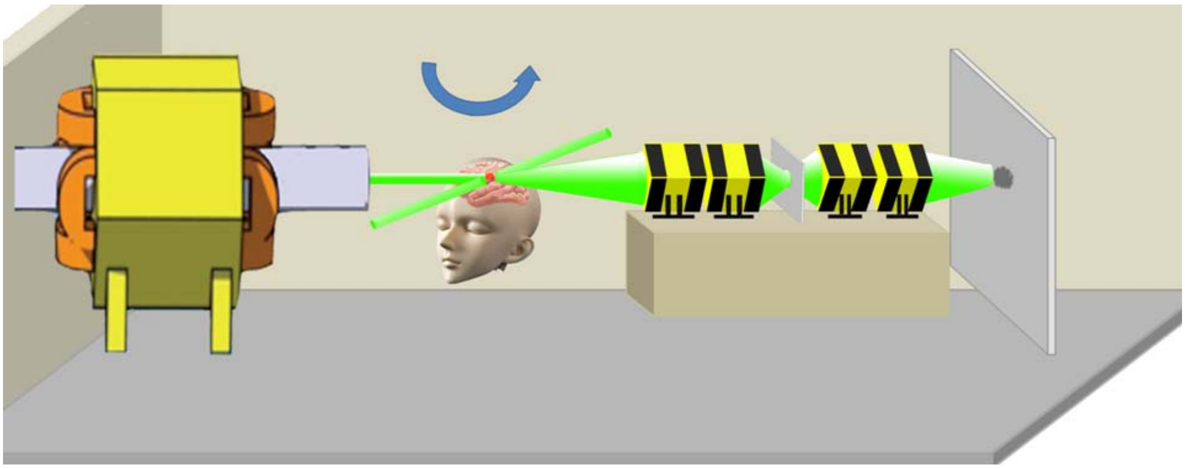

Figure 9: *Proposed setup for image-guided stereotactic particle radiosurgery at FAIR [5].*

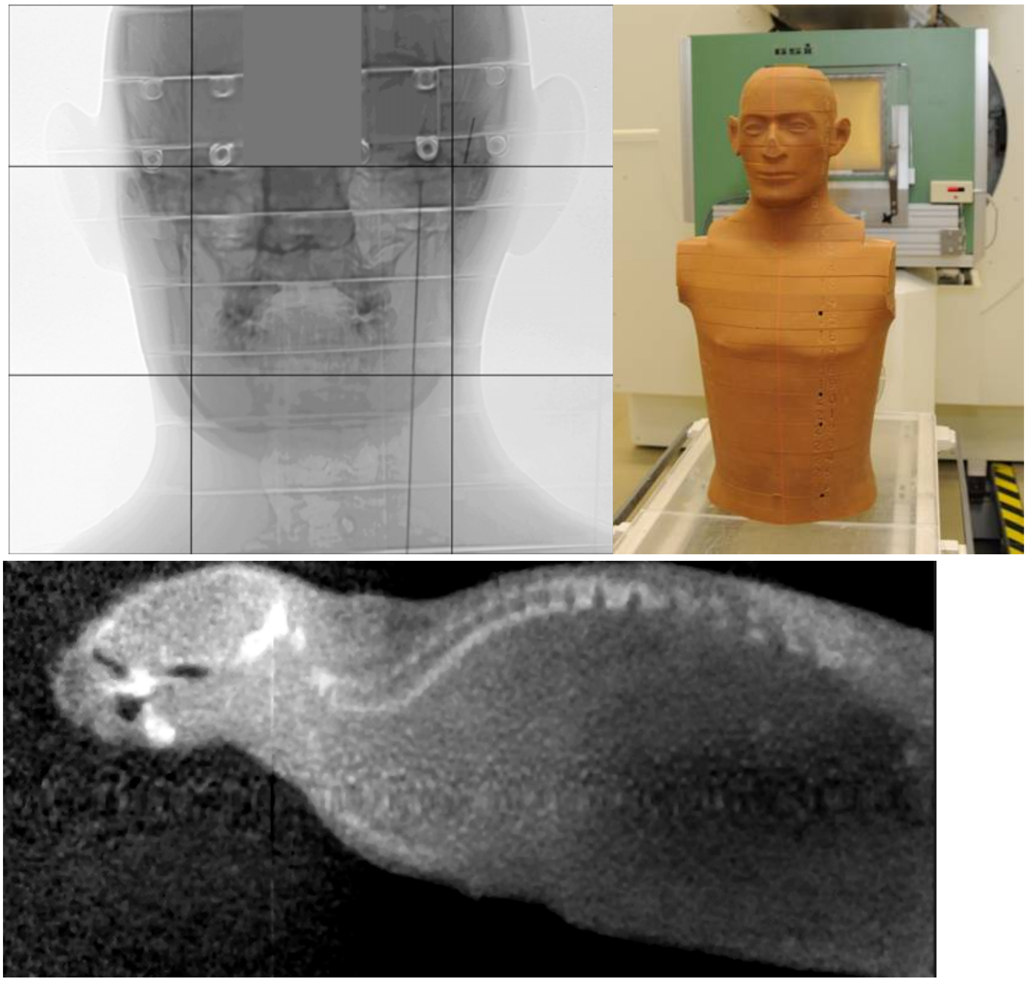

Figure 10: *Image obtained with high-energy proton microscopy (800 MeV protons, LANL, USA). The head of an anthropomorphic phantom and a longitudinal section of a mouse are shown. Resolution will be much higher at the FAIR facility. Press release* https://www.gsi.de/de/start/aktuelles/detailseite/datum/2013/06/03/tumoren-erkennen-und-behandeln-mit-protonen.htm?nr=805

[illegible] osed [illegible] y in [illegible] eak region. This idea has been previously explored at CERN with a low energy and low dose-rate antiproton beam (ACE experiment). We are now studying the possibility to use the FAIR beam for more realistic tests including animal experiments and a theranostic approach, where we will build position-sensitive detectors for the π-mesons and γ-rays which result from annihilation, to reconstruct the interaction vertex and therefore the energy deposited in the target. FAIR will therefore be the main European laboratory for testing innovative, breakthrough particle therapy applications [7].

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Materials Research

The Materials Research collaboration (more than 50 members from 7 countries) focuses on interaction processes of relativistic heavy ions and condensed matter, a complex interplay between multiple length and time scales. Effects include the emission of secondary particles and phonons, local melting, shock waves and permanent changes of materials properties.

FAIR beams will provide a unique tool to study the behavior of materials under multiple extreme conditions by combining ion irradiation simultaneously with the application of pressure and temperature (Fig. 11). During the past few years, the investigation of materials at high pressure has become an important focus in materials science (yielding new synthesis routes for materials with advanced electrical and mechanical properties) and in mineral physics (connecting mineral properties and geodynamic processes). An innovative experimental approach has been successfully developed at SIS18 which allows us to expose samples enclosed in diamond-anvil cells to relativistic ion beams (Fig. 11). High pressure and high temperature together with the extreme energy depositions from ion beams (energy loss of ions) drives the local atomic structure far from equilibrium which results in novel material modifications, such as the formation of new phases [1-3].

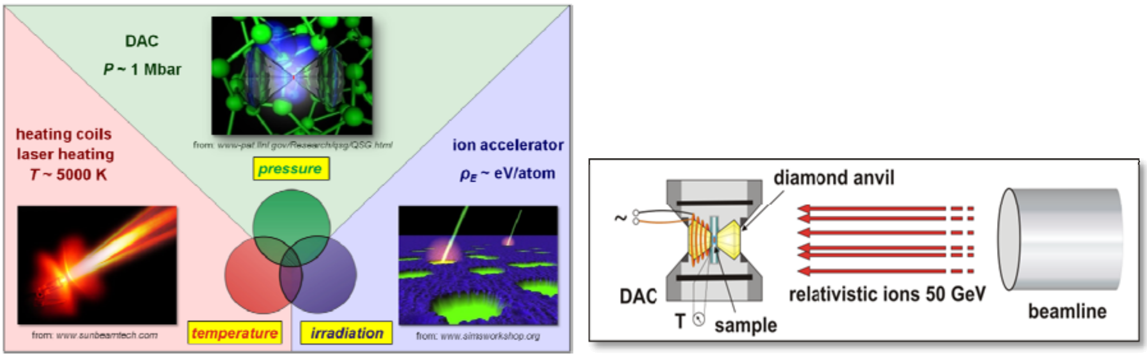

Figure 11: *The key strategy is to couple several extreme conditions such as ion irradiation, pressure, and temperature and investigate the specific response of a given material (left). Scheme of high-pressure irradiation experiments using relativistic heavy ions and high-pressure cells (right). The sample is pressurized between two diamond anvils, temperature can be applied by heating wires or by laser heating.*

The expanded ion range and the high intensity of FAIR beams provide unique access to modify solids by means that are unachievable using conventional materials processing methods. The novel behaviour of materials exposed to combined extreme conditions leads to exciting applications in the fields of solid state physics, materials research, nanoscience, and geophysics. High pressure and high temperature together with relativistic heavy ion beams can be used to form and stabilize new phases, to manipulate the physical and chemical properties of solids at the nanoscale, and to investigate the effects of radioactive decay events in compressed and heated minerals of Earth's deep interior.

Beam-induced radiation damage

In recent years, the ion-beam community has accumulated profound knowledge about on-line monitoring of beam-induced material changes, i.e., during irradiation and/or in-situ during beam stops. The expertise is largely based on experiments performed at the M-branch (UNILAC) and at cave A (SIS18). At present, various materials for FAIR components are being tested including organic insulators for application in superconductive magnets at cryogenic temperatures [4], various carbon-based materials such as graphite for Super-FRS production target [5], stripper foils, beam dumps, and composite materials for collimators. The investigations provide insight into physical and chemical property changes as a function of beam intensity and dose as well as energy and mass of the ions. Functional tests concentrate in particular on mechanical stability [6, 7] (Fig. 12) as well as on thermal and electric conductivity [8] changes. To avoid unexpected breakdown of functional materials in the harsh radiation environment at FAIR, pre-screening of extended dose effects is mandatory. The data base on damage effects coupled with simulations will allow us to select most suitable materials, optimize the design of FAIR components, and provide data for lifetime estimates.

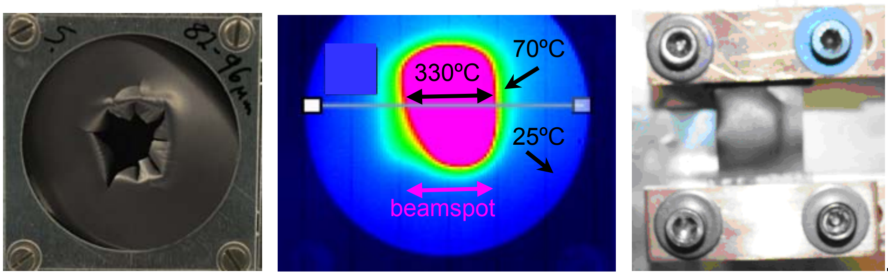

Figure 12: *Graphite samples exposed to a focused, high-intensity beam of gold ions (experiments performed at M-branch (UNILAC)): (left) target showing beam-induced disruption, (centre) temperature profile of beam spot recoded with a fast, triggered thermal camera, (right) beam-induced mechanical deformation.*

Progress report

The majority of irradiation experiments at the APPA cave can be performed in air behind the beam line exit-window. A prototype of a sample stage with remote control positioning is in preparation. For in-vacuum irradiations, equipment (e.g. heating or cryo-stage, spectroscopy methods, etc.) available from M-branch and Cave A experiments will be adopted.

The initial research plan (see CDR) of using a large hydrostatic pressure cell for pressure application was abandoned. Test experiments at the SIS18 revealed severe activation of components that prevent multiple use of the pressure cell within a given beam time. Alternative strategies are being prepared by combining standard diamond-anvil cells with Paris-Edinburgh type pressure apparatuses. This will allow the irradiation of larger samples at high pressure by monitoring induced structural modifications with x-ray diffraction and Raman spectroscopy.

The realisation of a technical design report concerning the irradiation infrastructure in the high energy APPA cave at FAIR is in progress. The final version is expected to be ready for submission durng the first half of 2013.

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