

EMMI Workshop Report: Plasma Physics at FAIR

An update to the Scientific Case for Plasma Physics at FAIR

The plasma physics department of GSI organized a workshop on plasma physics at FAIR on July 11th-13th 2016. That workshop, that has been sponsored by EMMI, HI-Jena and the plasma physics department of GSI, has gathered the plasma physics community to discuss actual topics in plasma physics and other related areas in order to actualize the science program for the plasma physics target station at FAIR. Below is a summary of the main topics of the meeting.

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1. Workshop Summary and Recommended Actions (Mehlhorn/Schoenberg)

The EMMI Workshop was well organized, well attended by a good cross section of international scientists, and precisely what was needed to begin an update of plasma physics related experiments using the APPA capability at FAIR. The workshop co-chairs (Dr. Vincent Bagnoud and Prof. Dieter Hoffmann) along with the local organizing committee and international advisory committee should be commended for a job well done.

The EMMI workshop was very important and successful, but it is only the first step. This Workshop Report fulfills the first suggested summary action, namely that a workshop document should be prepared to capture and preserve the information that was presented. This information should also be shared with FAIR/GSI management. Another step will be to hold a continuing series of workshops to clarify the scientific case and to develop detailed implementation plans. This will require meetings by a number of focused subgroups, as well as larger workshops to integrate the goals and plans of the subgroups into an overall plan for Plasma Physics at FAIR. In developing and integrating the subgroup input, it is critical that the community unite behind the shared goal of making the Plasma Physics Program at FAIR be a success. The first priority is to have the accelerator performance, APPA experimental components, and diagnostics in place to enable a unique and successful “Day One” plasma physics experiment at FAIR. If the Program is a success, each Project will have an opportunity to succeed on their specific research program. As successes accumulate, it will be easier to make the case for attracting additional resources to expand the experimental capabilities and diagnostics that will make FAIR an increasingly unique facility for Plasma Physics.

The Day One accelerator capabilities required by Plasma Physics at FAIR are derived from three classes of experiments:

1. Heavy ion beams (U^{28+} , 2 GeV, $10^{10} - 5 \times 10^{11}$) focused to a sufficiently high intensity by a superconducting quadrupole final focusing system to achieve uniform quasi-isochoric heating of a large volume, dense target and isentropic expansion (HIHEX). This will enable the measurement of EOS and transport properties for non-ideal plasmas and warm dense matter (WDM).
2. Heavy ion beams (U^{28+} , 1 GeV, 5×10^{11}) deflected into a ring-shaped beam by an RF “wobbler” that can heat a heavy cylindrical shell, causing it to implode and achieve a low-entropy compression of hydrogen. This will enable studies of hydrogen at Mbar pressures and moderate temperatures, typical of planetary interiors.
3. High-energy proton beams (p, 4-10 GeV, 2×10^{12}) configured as a unique, high-energy proton microscope with the SIS-100 beam to enable imaging of dynamic HEDP experiments, as well Proton Therapy and Radiography (PaNTERA) with the BIOMAT collaboration.

Each of these distinct accelerator capabilities enables a unique class of plasma physics experiments. We recommend that all the accelerator components to enable these three classes of experiments should be ready for Day One experiments. In particular, this will require a timely decision to finance the construction, testing, and commissioning of the wobbler, which is the critical enabler of the LAPLAS class of experiments.

It will also be important to have sufficient measurement capabilities on Day One to perform experiments with high scientific content including optical, x-ray and XUV, and particle diagnostics. The 100J laser system at APPA is particularly important in that it can serve as both a diagnostic for HIHEX and LAPLAS, as well a means to create shocked and high energy density matter that can be probed by PRIOR.

The scope of plasma-based research enabled by Day One FAIR is truly impressive and spans a range from Equation-of-State of materials in extremes (MatEx) to Warm Dense Matter (WDM) to Biophysics. Each of these areas has a unique set of experimental, theoretical, and computational requirements that derive from the ensemble of proposed experiments by

collaborators and users. (*For example: the specific states of matter that need to be formed, the parameters that need to be measured with specified accuracy, the theoretical and computational requirements required to interpret the data, etc.?*) This total set of requirements constitutes what can be called the Scientific Functional Requirements (SFR) for Plasma Physics at FAIR. While the Plasma Physics collaboration at FAIR has a good idea of scope of the required Day One capabilities, the project would benefit from adopting the process established for the MaRIE (Matter- Radiation Interactions in Extremes) project at Los Alamos and develop an ensemble SFR document that formally collates the requirements of each class of experiments. Culling this information from Workshop presentations and attendees can be a first step. However, we expect that more focused “topical” workshops, on specific areas of Plasma-based research, will be required to develop the complete set of Scientific Functional Requirements.

Once the SFRs are established, they can then be used to develop the Facility Functional Requirements (FFR) for Plasma Physics at APPA. That is, the SFRs specify the facility requirements for drivers (such as lasers), diagnostics, accelerator operating parameters, etc. While the SFRs for Day One capabilities will be resource constrained, to fully realize the possibilities of Plasma Physics at FAIR it will be necessary to be bold and expand the vision. These enhanced SFRs can be used to develop an enhanced set of FFR's can then be cross-walked with the existing FAIR APPA plans to identify “gaps” in facility capabilities. These “capability gaps” then form the basis set for requests to collaborators or government funded programs for additional resources to address facility performance shortfalls. Plasma Physics at FAIR will be in competition with XFELs, MaRIE, and other HEDP facilities. It can be competitive and provide unique capabilities, but additional investments beyond Day One will be necessary.

Developing a comprehensive suite of diagnostics will be critical to attaining high scientific output for Plasma Physics at FAIR – the program must be bold and have a long-term vision. The SFR-FFR process will be useful in planning facility improvements. However, from the presentations made at the EMMI workshop, three things stand out for additional consideration. First, adding a ps option to the 100J laser at APPA will provide valuable capabilities and can be accomplished in the near term. Second, the kJ laser (Helmholtz Beamline at FAIR) is essential and can be developed in collaboration with the Helmholtz International Beamline for Extreme Fields (HIBEF) at the European XFEL. To be scientifically competitive, FAIR will need the same laser-based diagnostic capabilities as XFEL. The two facilities will have complementary HEDP heating capabilities (heavy ions vice photons) and should have comparable diagnostic capabilities. Finally, in order to save money, APPA only has one beam line for both heavy ions (HIHEX and LAPLAS) and protons (PRIOR). However, one should not forget the original concept of two beam lines to enable proton radiography of heavy-ion-heated samples as a long-term option.

Thus far, this summary has primarily focused on accelerator and diagnostic issues, since these are on the critical path for resources and construction. It is also important to consider the broader presentations made at the EMMI workshop. In particular, the workshop contained excellent presentations on the theoretical questions that can be answered through Plasma Physics at FAIR. Plasma Physics at FAIR should follow the modern scientific paradigm of having an environment where there is a rich dialog between theory and experiments. A vibrant Plasma Physics program will include theoreticians, code developers, designers, experimenters, and diagnosticians, all teaming to perform experiments on the most important scientific questions. The Plasma Physics community will benefit from sharing of simulation codes, EOS tables, and related databases, as well as analysis and post-processing tools. Plasma Physics at FAIR can play an important role in improving the science of Warm Dense Matter (WDM) by more tightly coupling the theoretical, experimental, and diagnostic communities. The study of WDM requires unifying theoretical frameworks in order to guide the design of highly diagnosed experiments that test the theories and close the data gaps. The data can then be incorporated into improved models that can be applied in many ways – e.g. the development of improved planetary models.

In addition to the scientific, technical, and facility issues discussed in this report, Plasma Physics at FAIR also has issues in manpower and leadership that need to be addressed. This will be done in a separate document.

2. Scope of the Meeting

The Workshop on Plasma Physics at FAIR was held at GSI Darmstadt on July 11th-13th, 2016 to review the status of international research in HED/WDM and explore the important scientific questions that remain to be answered; to discuss the planned capabilities for Plasma Physics at FAIR and to discuss proposed experiments; and to found a new Plasma Physics collaboration at FAIR/GSI. The workshop was attended by over 100 scientists from 13 countries. This report summarizes the content of this EMMI Workshop and is intended to serve as a resource for updating the scientific case for Plasma Physics at FAIR and for answering the scientific questions posed by Dr. Boris Sharkov, Scientific Director of FAIR. The intent of this report is to capture and preserve the information from this workshop and to share it with FAIR/GSI management, as well as the newly founded plasma physics collaboration. This information will be used by participants at a future workshop to answer Dr. Sharkov's questions and to formulate an updated scientific program for Plasma Physics at FAIR/GSI.

1.1 The FAIR Project and Questions for Plasma Physics

The following are the list of questions that Dr. Boris Sharkov posed to the Plasma Physics community.

- What are the burning plasma physics questions which FAIR can answer and which cannot be addressed at any other facility?
- How is plasma physics at FAIR embedded into the international landscape of plasma physics projects (LCLS, XFEL, NIF, etc.)? Are there any co-operations ongoing or planned?
- What is the early research (Day-1) program which can be addressed once the SIS100 is operational?
 - Which instrumentation is needed to achieve this goal?
 - What is the time line for the construction and commissioning of the Day-1 detector components?
 - How is the needed financing of these components guaranteed?
- Which intermediate research program (FAIR Phase-0) is envisioned at GSI until the SIS100 is operational? Will this be supplemented by activities at other facilities?

3. Plasma Physics at FAIR (Bagnoud/Blazevic)

1.2 Plasma Physics at FAIR: D. Riley

Plasma physics is an important aspect of physics that helps understanding our world and also finds a wide spectrum of applications. Therefore the number of existing or planned facilities worldwide dedicated to plasma physics is large. These facilities are using various drivers from optical lasers, Z-pinches and X-ray lasers to Gas guns and are able to cover complementary aspects of plasma physics studies like shock physics, warm dense matter and dense plasma. FAIR is going to add a complementary approach to these facilities in a parameter range relevant to warm dense matter that is very attractive and competitive compared to the other existing methods. In particular, studying strongly coupled plasmas, which are hard to describe theoretically and are relevant to describing the interior of giant planets like Jupiter [1] for instance, is going to fall ideally within reach of FAIR-driven plasma parameters.

¹ N. Nettelmann et al., *Astrophysical Journal* **683**, 1217 (2008)

The properties of warm dense matter generated by ion beams are very desirable to make high-precision studies. These unique properties include a large millimeter-sized scale that enables slower time scales and close to thermodynamical equilibrium conditions and a very high sample uniformity. This contrasts for instance with laser-driven plasma that are characterized by extreme gradients in temperature, pressure and densities and also suffer from sample pre-heating caused by fast electrons and hard x-rays in the case when shock are studied.

In addition, the samples generated by the FAIR beams are created in a very quiet background, with the only background coming from the sample self-emission. In laser-driven WDM studies, the laser radiation is converted to X-rays that in turns heat the sample volumetrically. In addition to the non-uniform absorption of X-rays in matter leading to plasma non-uniformities, the plasma responsible for the X-ray generation represents a huge background noise that needs to be overcome and seriously impair precise measurement abilities.

1.3 The experimental facility for plasma physics at FAIR: A. Blazevic

As a host lab, GSI is coordinating the technical implementation of the plasma physics capabilities at FAIR. These activities are centered on the three main plasma physics schemes using FAIR beams: isochoric heating and expansion, compression experiments and proton microscopy (PRIOR). The experiments will take place in the APPA cave, a 1064 m² fully shielded laboratory space shared by the APPA collaborations: plasma physics, atomic physics, materials research and biophysics. While the latter share a single beam line, the plasma physics community will “own” a dedicated beamline that need to accommodate all three experimental schemes.

At the heart of the plasma physics beamline, the final focusing magnet will allow reaching the necessary beam shapes. This component is being finalized with the construction planed in Russia (IHEP) and the interface and auxiliary elements provided by FAIR. In addition to the focusing magnet, a wobbler will be employed to create the ring-like ion intensity distribution for compression experiments.

For Prior, a prototype (PRIOR I) has been successfully commissioned at GSI in the high-energy cave (HHT) in the last years. This work represents a solid base for the TDR of the final PRIOR setup that will avoid the shortcomings of PRIOR I. In particular, electro-magnets will be used instead of permanent magnets that degrade quickly in the accelerator environment. The use of a single beamline for all three schemes imposes a strong constraint on the experimental layout. The current layout is able to support all three experimental setup but requires some tuning between experimental campaigns that will prevent switching from one to the other experiment rapidly. Therefore, it is expected that experimental setups will be operated in sequences of several months rather than on a short cycle basis.

Most of the high-energy density experiments will happen in a target chamber whose design is being finalized right now. The main issue with the target chamber is the extremely high requirements coming from millimeter-sized targets that create large shocks and debris. The debris are not only problematic from a ballistic damage stand-point but they represent a large quantities of dust, particles and evaporated material that will be activated and must be taken care of.

In addition to the main beamline elements, a series of diagnostics representing a significant investment effort and a 100 J laser will be implemented at the APPA cave for the day-one experiments. These aspects are essential parts to the success of the start of the facility. Indeed, power diagnostics and the possibility to realize pump-probe setup are vital to deliver the first scientific results. For the mid-term, the Helmholtz-beamline should be filling this role, fully allowing exploiting the potential of the plasma physics beamline.

1.4 The FAIR Accelerators: P. Spiller

Peter Spiller from GSI presented on Tuesday the status of the existing accelerator with SIS18, the upgrade measures and the outlook on its capabilities in future, followed by the progress of building up SIS100 and its expected parameters relevant for the plasma physics program.

He pointed out that as consequence of the SIS18 upgrade program 2005-2013, including the integration of a new injection septum, low absorption catchers, NEG coatings in magnet chambers, etc., the space charge limit for many light ions is reached, whereas for the heavy ions it is missed by a factor of 10. Therefore to insure the designed parameters for FAIR operation (U at 200 MeV/u, $I = 1.5 \times 10^{11}$ p/spill, $f = 2.7$ Hz) it was decided to switch to intermediate projectile charge states and hence to enhance the space charge limit. This was successfully demonstrated with an U^{28+} ion beam reaching intensities of more than 3×10^{10} particles in the SIS18 ring. This means that an intensity of $1-2 \times 10^{11}$ p/spill is safe for the commissioning of SIS100, even though further upgrade measures are required for reaching the goal for the most heavy ions and the repetition rate of 2.7 Hz. Additionally the intensity for protons could be increased significantly.

In 2017 there will be no accelerator operation due to further upgrades of the UNILAC and SIS18. For the last one the link of the existing facility to the FAIR tunnel 101 with some radiation protection improvements and shielding enhancement is foreseen. From 2018 on a staged ion beam intensity increase is planned. Till 2021 SIS18 will run with protons ($E < 4.7$ GeV, $I < 10^{12}$ p/spill, $f = 1$ Hz) up to highly charged ions (e.g. U^{73+} , $E < 1$ GeV/u, $I < 1.5 \times 10^{10}$ p/spill, $f = 1$ Hz). Beyond 2021 the ring will be operated in the booster mode delivering protons with $E < 4.7$ GeV, $I < 6 \times 10^{12}$ p/spill, $f = 2.2$ Hz or heavy ions with intermediate charges like U^{28+} , $E < 0.2$ GeV/u, $I < 1.5 \times 10^{11}$ p/spill, $f = 2.7$ Hz optimized as injector for SIS100.

The procurement of the SIS100 synchrotron components is progressing well. All major magnets, all main RF components (e.g. bunch compressors) and all injection devices are under contract (65% of SIS100 value). Several components are already in the phase of serial production, like the super conducting dipole and quadrupole magnets. As cooling in SIS100 with electrons or stochastically will not be possible the accelerator group is investigating in collaboration with the atomic physics department the possibility to cool down relativistic heavy ions with a laser beam for being able to extract very cold and very short relativistic ion bunches. This can be used for ions with $Z = 10 - 60$ (3 - 19 bound electrons).

For both, SIS18 and SIS100 forefront developments have been launched to further improve the beam performance relevant for plasma physics and the other collaborations.

1.5 Russian contribution at Plasma Physics@FAIR: A. Golubev

Alexander Golubev from ITEP, Moscow, reported about the contributions of the 11 Russian institutes to the plasma physics program at FAIR covering the expressions of interest for core invest as well as active participation on planed experiments at HHT, PHELIX and FAIR, and summarized the minutes from the last meeting of the Russian part of the collaboration on HED physics at FAIR.

The Russian part of the collaboration has expressed their interest to apply for funding, to build and deliver as Russian in-kind the following items:

Institute	System & description	Status
IHEP	Superconducting large aperture Quadrupoles	Assigned by the FAIR Council on 2014. The technical specifications for the SC final focusing system have been submitted to FAIR. The contract negotiations between FAIR and IHEP have started.
ITEP	Wobbler	TDR on Wobbler was approved by FAIR ECE in 2015.
ITEP	PRIOR magnetic system	The design for the PRIOR magnet system has been finished. TDR is expected to be ready in 2016.

IPCP	Target chamber	TDR is expected to be ready in 2017.
Lebedev Physical Institute	LAPLAS cryogenic target	TDR is expected to be ready in 2017.

Table 1: Expression of interest from the Russian part of the collaboration and status of the respective work packages

Additionally he pointed out that for the wobblers comprehensive 3D numerical simulation were performed to get a most realistic picture of the process and simulation algorithms were benchmarked with already published simulation results. The results show that the high compression stage is not very sensitive to uniformity demands on the beam and that LAPLAS is able to achieve the required parameters. But it is necessary to accelerate the decision concerning the funding of the project.

Concerning the target chamber, he addressed once more the interest of the Russian community in a target chamber for experiments with explosive generators.

In the second part, of the talk A. Golubev reported on the Meeting of the Russian part of collaboration on HED-physics at FAIR which was held on May, 12th in ITEP. During the meeting the current status of Phase "0" and Phase "1" experimental programs and important steps which have to be done by the collaboration in preparation of the forthcoming experiments were discussed. More than 40 participants from the scientific and educational institutes took part in the meeting: JIHT RAS (Moscow), IPCP RAS (Chernogolovka), LPI RAS (Moscow), ITEP (Moscow), NRNU, MEPhI (Moscow), GSI (Darmstadt).

Discussion summary:

1. The physical program of HEDgeHOB collaboration for HIHEX and LAPLAS experiments remains actual, and it has to be discussed in more details taking into account the heavy ion beam capabilities at all phases of the FAIR project.
2. The Russian part of the collaboration ensures its great interest on the Plasma Physics program at GSI and FAIR and its intention to further active experimental and theoretical support based on its long term experience in this field.
3. Within the phase "0" of the FAIR project we support the scientific program which includes:
 - a. **Experiments at HHT:** Equation of state, theoretical modeling of the experimental conditions using SIS18 heavy ion beam parameters for optimization of experimental schemes, study of phase transitions in samples, investigation of phase transitions in molecular liquids (N₂, H₂) at high pressures by proton radiography, equation of state of shock compressed non-ideal strongly coupled xenon plasma by means of proton microscope PRIOR.
 - b. **PHELIX/Z6 experimental area:** investigation of phase transitions in laser-driven warm dense matter relevant for planetary science, development of laser-based plasma diagnostics, intensive theoretical support of experiments on laser-plasma interaction.
 - c. **Day-one experiments:** HIHEX experiments with uranium beams, proton radiography for measurements of the target density distribution in dynamic experiments, explosive target chamber in combination with the proton radiography for precise density measurements, which will guaranty a novel top scientific level of EOS-data.
4. The Russian part of collaboration strongly supports the idea of founding a new collaboration for Plasma Physics at FAIR (PP@FAIR)

4. Physics Issues in HED and WDM (D. Gericke)

This theory session contained 5 talks that cover a large range of theory and simulation issues in high-energy-density matter: finite-temperature contributions in ab-initio simulations,

classical simulation techniques modified to include bound state behavior, collective properties of (screened) Coulomb systems, transport and kinetic relaxation processes as well as the theoretical basis for x-ray Thomson scattering. In warm dense matter, such modelling and simulation capabilities need to cover both theoretical predictions to be tested by experiments as well as theoretical support for the design, analysis and interpretation of experiments. The presented work covered this full range.

Bonitz's talk covered the core questions of first principle simulations. Here, a quantum Monte Carlo approach for the electron gas at finite temperatures was presented. The main step forward was the construction of an approach that can handle weak quantum degeneracy as well as the highly degenerate electron gas. On this basis, new finite-temperature correlation potentials can be constructed which can then serve as input for density functional simulations for fully coupled electron-ion systems.

The talk by Calisti showed the opposite approach as here classical molecular dynamics simulations were employed. The quantum behavior of the electrons is here introduced by an ad hoc term in the interaction potential that is linked to ionization energies. Although the model carries the usual issues of mimicking quantum mechanics by local potentials, it has the large advantage that dynamical processes can be investigated. Results for the dynamic structure factor, related to scattering experiments, as well as the depression of the ionization energy due to the interacting environment were shown.

Tikhonchuk presented results for transport phenomena and instabilities in magnetized plasmas based on kinetic equations. The growth of instabilities in streaming matter is a core question of plasma physics. Results were shown for the stream instability and the heat flow in magnetized matter. In the latter case, the magnetic field acts as a transport barrier as it restricts the motion of the free electrons along the field lines (only collisions can then result in perpendicular transport).

The contribution by Tkachenko covered recent developments on collective modes in dense systems of charged particles. The dispersion of these collective excitations is a very sensitive probe for the micro-physics within the plasma. Moreover, the modes link exact theoretical results (sum rules) to measurable quantities. It was shown how the sum rules can be used to construct the full dielectric response and the dynamic structure factor. Examples were given for model systems like the one component plasma model and the Yukawa system including screening.

The theoretical basis of X-ray Thomson scattering was discussed in the talk by Witte with special emphasis on the plasmon dispersion. The presented approach is mainly based on density functional theory coupled to molecular dynamics for the ions. Thus, it links ab initio modelling to the interpretation of scattering signals. Interestingly, different exchange-correlation potentials give quite different results for the damping of the plasmons. This quantity can then be developed into a theory for the conductivity and compared to the measurements yielding a critical test of the main input of DFT.

5. Ion-Beam Facilities (Varentsov)

1.6 Status of PRIOR: D. Varentsov

Dmitry Varentsov from GSI reported on the recent successful beam time commissioning of the PRIOR-I (Proton Microscope for FAIR) proton microscope at GSI. PRIOR-I is the prototype of the future PRIOR facility and it employs high-gradient (120 T/m) NdFeB permanent magnet quadrupole (PMQ) lenses. The PRIOR-I setup has been fielded at the HHT area of GSI to assess the capabilities of PRIOR with SIS-18 3.5–4.5 GeV proton beams. The static commissioning of the PRIOR-I prototype has demonstrated 30 μm spatial resolution with remarkable density sensitivity. For dynamic commissioning, a new pulsed power generator (50 kV, 12 μF) has been constructed and installed at HHT for underwater electrical wire

explosion experiments. During the dynamic commissioning run, 0.8 mm diameter exploding (180 kA, 1.3 μ s rise time) Ta wires have been radiographed by PRIOR-I using 3.6 GeV proton beam. A temporal resolution of 5–10 ns has been achieved and the expansion of the Ta plasma at different specific power deposition levels up to 10 GW/g has been compared with optical measurements.

The PRIOR-I commissioning experiments have indicated that the PMQ lenses are not an appropriate choice for the final design of the PRIOR facility due to the severe radiation damage of the PQM magnets. Therefore the final design of the PRIOR proton microscope (PRIOR-II) employs small but strong and radiation-resistant electromagnets (60 mm aperture and 1.3 T pole tip field). The design of these new magnets has been presented along with the ion-optical design of PRIOR-II. The design assumes that the PRIOR-II setup will be first fielded at the HHT area of GSI to use up to 4 GeV protons delivered by the SIS-18 synchrotron for static or dynamic experiments, and later will be transferred without modifications to the new experimental area at FAIR and used with intense 2–5 GeV proton beams of the SIS-100 synchrotron. The PRIOR-II facility will provide a magnification of about 3.5 at GSI and up to 8 at FAIR with 10 μ m spatial resolution at the object. The first experiments with the PRIOR-II facility at GSI are planned for the end of 2018.

1.7 Proton Radiography and Tomography of Biological Samples: M. Prall

Matthias Prall from the biophysics department of GSI presented the PaNTERA (Proton Therapy and Radiography) joint project of GSI, LANL and DLR. First, he gave an overview on proton imaging in medicine emphasizing a big potential of the proton microscopy with its unique advantages in stereotactic image-guided radiosurgery (simultaneous proton imaging and treatment) and in proton CT. The results of the joint experiments at LANL (800 MeV pRad facility) on the topic were shown and discussed: high-resolution proton radiographs and proton CTs of the Matroshka human phantom and other biological samples (chicken, mouse, zebrafish). The plans for further developing of the PaNTERA project and the future experiments at GSI and at FAIR using the PRIOR facility were revealed.

1.8 Compressed, Short-Pulse Ion Beams at the Neutralized Drift Compression Experiment: P. Seidl

Peter Seidl from LLBNL, USA communicated on recent developments and progress of the Neutralized Drift Compression Experiment -II (NDCX-II) at LBNL, USA. Compressed, short-pulse ion beams have been generated at NDCX-II after integrating and commissioning all its components. The ns-long 1.2 MeV Li^+ pulses are available with 10^{20} ions/cm/s peak dose rates and 1.4 mm FWHM spot. A new plasma ion source provides 50 mA of He^+ ions. At the moment 2–15 nC/pulse, 2–40 ns-long ion pulses focused to $r = 1$ mm spot are available for target experiments with about 1 pulse/minute repetition rate. The current research goals at NDCX-II are improving the understanding of intense beam physics, testing radiation effects on various materials and equation-of-state studies of warm dense matter around 1 eV temperature, making complimentary research to science with lasers and laser-generated ion pulses. LBNL welcomes visitors and collaborations for new experiments with NDCX-II facility.

6. The International Landscape of HED/WDM Physics Research (Golubev)

Three reports have been submitted during this session Landscape of HED/WDM physics research in Europe, Russia and America presented by V. Tikhonchuk (University of Bordeaux, France), V. Mintsev and T. Mehlhorn (Naval Research Lab., USA)

The European activities in the High Energy density physics were presented by V. Tikhonchuk. They address issues and processes in matter at extreme conditions: pressures > 1 Mbar, temperatures > 1 eV, densities > 1 g/cc. They are driven by fundamental research and high-

profile applications: inertial confinement fusion for energy production (IFE); laser plasma interactions and nonlinear optics in plasmas (LPI); radiation hydrodynamics and strong shocks > 100 Mbar; equation of state modeling for the planetary science – phase transitions; radiation opacities for solar physics and astrophysics; generation of strong magnetic fields and their effects on hydrodynamics; new diagnostic techniques: soft x-ray XANES², Thomson scattering, hard x-ray radiography; nuclear physics in short time scales: stopping power, reaction rates; quantum electrodynamics: γ -sources, QED in matter, particle acceleration.

Europe hosts a largest park of HEDP installation covering an extremely wide energy range and sources. They are coordinated within the European programs such as LASERLAB, COST and ESFRI. However the resources are limited leading to certain delays in construction. Research is conducted in collaboration with similar laser facilities in the USA and Japan. The research activities in Europe are concerning main stream applications: inertial confinement fusion in direct drive geometry, generation of strong shocks with energetic laser and electron beams and generation of strong quasi-static magnetic fields with intense laser pulses. Concerning the warm dense matter studies, a significant progress has been achieved with the development of a technique of laser isentropic compression and XANES by combining the laser and X-FEL beams. New perspectives are opening with the recent measurements of the ion stopping power in non-ideal plasmas and near the Bragg peak energy, using the secondary laser driven sources of charged particles (electrons and ions) and gamma-radiation for the radiography and studying nuclear reactions in the ps time scale.

The talk given by T. Mehlhorn from the US Naval Research Laboratory presented the landscape in America, HEDP research in NRL, and perspective collaborations using intense ion beams. T. Mehlhorn presented experimental data of the EOS of carbon, iron, and hydrogen and the structure (phase) of carbon under ramp compression to high pressure, which was being measured on NIF, ramp compression of diamond to five Terapascals carried out by a team from Princeton, UCB, and LLNL. Special attention in the report was devoted to the pulsed power Z machine facility in Sandia, which allows providing Mbar material experiments, to produce 2 MJ of x-rays for research on radiation effects on materials and fundamental properties of matter, to research of fundamental plasma physics and inertial fusion. The talk also presented an overview of HEDP activities on US laser facilities such as LLE in Rochester University and the Nike Kr-F laser facility, such as the measurement of EOS, opacity, thermal conductivity, shock and release, and the development of diagnostic techniques. At the Nike KrF laser facility thin foil targets were accelerated to greater than 1000km/s.

The talk given by V. Mintsev from ICPC RAS presented a review of the possibilities for the generation of non-ideal plasma with the help of heavy ions and, the prospect on proton radiography for measuring dense plasma parameters. Specific energies of 5-10 kJ/g, pressures of 1-2 GPa and temperatures of 1-2 eV are expected to be reached in the substance at the first experiments at FAIR. It will give possibility to investigate two-phase region including critical point of several metals in HIHEX (Heavy Ion Heating and Expansion) experiments with the plane and cylindrical geometry, realizing regimes of quasi-isochoric heating, isentropic expansion and compression when the flow strikes with the target. Analysis of thermal radiation transfer will give information about dynamics of vaporization. Measurements of the electrical conductivity and optical properties on supercritical adiabatic will give information about insulator to metal transition at these conditions. LAPLAS (Laboratory Planetary Sciences) experiments suggested compression of hydrogen and noble gases at initial cryogenic temperatures up to Megabar pressures to investigate possible non-ideal plasma phase transitions. Possibilities of stimulated Mach configuration to get Megabar pressure range are discussed. Much attention will be paid to proton radiography to be employed as a main diagnostic for direct measurements of density with high space and time resolution. Here, high-energy high-intensity proton beams will be available for the investigations of fundamental properties in materials in extreme dynamic environments

² XANES stands for X-ray Absorption Near Edge Spectroscopy

generated by external drivers (pulsed power drivers, high energy lasers, gas guns or HE generators). We will consider possibilities of explosively driven technique matched with proton radiography to investigate regions of plasma phase transitions in H_2 , D_2 , N_2 , rare gases, etc. at Megabar pressures and reveal the influence of strong Coulomb interaction on thermophysical properties of non-ideal plasma.

So within the phases "0" and "1" of the FAIR project we support the scientific program including:

- Equation of state studies using heavy-ion beams from SIS-18 to uniformly and quasi-isochoric heat macroscopic samples including porous metals and further expansion in gas at different pressures (HIHEX experiment). Recovery and modernization of diagnostic is needed, intense beam of U73+ with max intensity and energy 400 –1000 AMeV.
- Investigation of phase transitions in molecular liquids (N_2 , H_2) at high pressures by proton radiography. Equation of state of shock compressed non-ideal xenon plasma by means of proton microscope PRIOR. – Explosive chamber transfer from Z6 to HHT is needed, and the possibility of work with high explosives with mass up to 150 grams is required. Explosive target chamber with charges up to 1 kg TNT is needed to generate states with pressures more than 1 Mbar (which is necessary to reach the region of plasma phase transition) and possibility of work with high explosives with mass up to 1 kg is required

7. HED/WDM Facilities Worldwide (Bagnoud/Schoenberg)

In America, HED/WDM facilities are funded as part of the stockpile stewardship program of DOE that promotes ICF research. These facilities are the NIF at LLNL in California, Omega at LLE in Rochester, NY, the Z-machine at Sandia national Lab. in Albuquerque, NM, and the Nike KrF laser at NRL in Washington DC. In addition to these existing facilities, the MaRIE (Matter-Radiation Interaction in Extremes) project plans an extension of these studies done on the microscopic scale to the meso-scale with a strong impact on material research.

NIF can be used as a compression facility that creates spherical compression conditions in laser-heated hohlraums. The current scheme allows studying low-Z materials like carbon and hydrogen at high pressures using shock compression. Carbon up to 50 Mbars and CH near GigaBar have been measured allowing to explore areas of the equation of states (EOS) where the different plasma description models (Thomas-Fermi or DFT for instance) diverge significantly. Of course, these states are observed in shock experiments that are transient and not at perfect equilibrium but they bring a first answer to these outstanding questions. The Z-machine is a compression facility that finds applications in planetary science (moderate temperature, high pressure) where metal to insulator transitions of hydrogen are being studied for instance [3]. In addition to these two major facilities, Omega is an important training ground and diagnostic development platform for HED research in America.

For Europe, V. Tikhonchuk made a review of the HED facilities. These are mostly based on laser drivers with a suite of facilities in France (LMJ, Petal, LULI), the UK (Orion, Vulcan) and the new eastern countries developing the ELI pillars (Czech Republic, Hungary, Romania). Lasers may not be the ideal drivers to reach HED states as they create micrometer-small, highly transient, and non-uniform plasmas but they are still the most widely used because of their interest as drivers in ICF research. As a side effect, compression schemes and laser-based diagnostic methods emerge like XANES [4] that could later be applied at FAIR. In this sense this is rather a synergy between the existing facilities and FAIR that can emerge.

³ M. D. Knudson et al. Science **348** 1455 (2015)

⁴ F. Dorchies et al. Phys. Rev. B **92** 085117 (2015)

In America and soon in Europe, x-ray free electron lasers (FEL) offer an alternative to HED studies. Being a source of ultrashort coherent x-ray pulses, FELs are the ideal diagnostic to measure the structure of materials on the atomic scale. In addition, FELs have been proposed and used as HED drivers but the highly transient states obtained are opening a new field in its own rather than creating a direct competition to the nano- to microsecond long plasmas generated by the FAIR beams.

At the workshop, there was no overview given on the facilities in Asia because the foreseen speaker did not obtain the necessary travel document to attend the conference. Nevertheless, it should be pointed out that Asia is very active in the field with HED research in countries like China, Japan and South Korea.

1.9 Possible FAIR-MaRIE collaborations in HED Science: K. Schoenberg

The talk given by Kurt Schoenberg from LANL covered the proposed project MaRIE (Matter-Radiation Interaction in Extremes) in Los Alamos, the needs of MaRIE from their collaborators and the potential areas for a joint effort of MaRIE and FAIR and the collaborators, respectively.

MaRIE will be an international user facility specified on the research of materials in the extreme of temperature, pressure, and in radiation environment. Its goal is to investigate material properties, understand their compositions and to control the processing to be able to design materials, i.e. to develop new materials, to select specific functions for certain applications or to optimize the performance of a given material. Therefore at MaRIE scientists will be able to use a versatile set of probe beams as XFEL (42 – 126 keV, 2×10^{10} photons@50 fs, resolution $> 0.1 \mu\text{m}$), protons (800 MeV, 5 ns frame speed, resolution $< 10 \mu\text{m}$), electrons (12 GeV, 25 ns frame speed, resolution $\sim 1 \mu\text{m}$), neutrons and possibly high-intensity, short pulse lasers concentrated in two halls, a Making, Measuring and Modelling Facility for material synthesis and characterization, and a Multi-Probe Diagnostic Hall where the probes will be subjected to time-dependent extremes and where they will be probed by both, imaging and diffractive scattering methods to connect to the material performance. The extensive scientific case for MaRIE was demonstrated by some selected examples of non-ideal material response to dynamic compression or shocking. The investigations of additive manufacturing of complex shapes that are achieving very similar mechanical properties of traditional manufacturing but with different microstructure was presented as well as the different response of materials to dynamic forces leading to varying failure under e.g. high strain.

As next step in the project progress, after passing the DOE Critical Decision Zero in March 2016, the Technology Maturation Plan has to be elaborated. Among the major technology maturation elements there are listed components like laser probes and drivers, X-ray detectors, imaging detectors, thermometry or pRad imaging, showing a significant potential for joint Helmholtz-Los Alamos collaboration.

In the following Kurt Schoenberg evaluated potential areas for collaborating with Plasma Physics at FAIR and GSI. First he emphasizes the very successful and constructive existing collaboration on the development of charged particle radiography. This collaborative work covers common experiments at LANL as well as GSI, the improvement of experimental methods, the development of diagnostic tool as well as the improvement of simulation and data analyses codes. MaRIE Tech-Mat is interested in continuing the experimental work at LANL and GSI as part of a future PRIOR collaboration.

The second area covers the development of advanced Thermometry diagnostics such as NRS (neutron resonance spectroscopy) for time and spatially resolved measurement of bulk-temperature. This method needs an epithermal neutron beam ($\sim 20 \text{ eV}$) that could be produced by a laser, moderated in a solid moderator and then redirected to the sample and detected behind. This experiment could be performed as R&D at PHELIX.

Finally MaRIE as well as PP at FAIR will need a variety of drivers to create WDM. A common effort in developing and testing drivers is obvious. Especially the development of laser drivers

and probes is a field with a large overlap and good existing relations, where both partners would profit, e.g. by tackling technical problems like laser amplification, frequency conversion, repetition rate increase. This collaboration would ensure a credible cost and schedule estimate and therefore an affordable bid to build the needed laser.

8. Day-One Experiment Proposals for FAIR (Rosmej/Neumayer)

At the meeting on Tuesday afternoon, an overview of the day-one experiment proposal was done. The day-one experiments differentiate in whether they require the PRIOR or HIHEX setups. Only a short overview of the proposal was given with 10-minute presentations and it is clear that a much more in-depth work has to be done to bring these proposals from the conceptual level to a fully technically flushed level. In particular, it is one task of the upcoming FAIR plasma physics collaboration to coordinate that work. Below is a report on two of the seven day-one experiment proposals that were presented at the meeting.

Two day-1 experiment proposals by D. Gericke (U. Warwick) and P. Neumayer (GSI) were presented, which besides the first heavy-ion beams available in the APPA-cave would require the 100-Joule long-pulse laser system that is currently under discussion. Laser-plasmas generated with these laser parameters are well-established robust and repeatable sources of intense few-keV x-ray emission. The presented proposals foresee such an x-ray source as diagnostic to probe the structure and electronic states of the heavy-ion heated samples.

1.10 Ionization potential depression in the low density limit

The proposal “Ionization potential depression in the low density limit” aims at measuring the ionization potential depression (IPD) in an aluminium plasma at densities ranging from solid down to $1/10^{\text{th}}$ of solid density (temperatures up to 1eV). A hot, high-Z plasma generated by the energetic laser pulse will provide a broadband continuum x-ray source in the spectral range of 1.5-2keV, which will be used to perform absorption spectroscopy on the heavy-ion produced Al-plasma. Atomic kinetic calculations incorporating the famous Stewart&Pyatt-model for IPD show that the change of the IPD can be assessed by a shifting of the absorption K-edge. In addition, M- and N-shell rebinding would be seen by additional absorption lines of the $(1\rightarrow3)$ and $(1\rightarrow4)$ -transition. This would constitute the direct observation of the transition from a hot metal to a dense atomic gas. While Al-plasmas generated with FAIR HI-beams would certainly not be the densest or hottest plasmas, compared to those produced at other large-scale HED facilities, they represent a strongly-coupled, near-degenerate plasma, i.e. a sample at warm-dense matter conditions, where current theoretical models are expected to fail. This has been highlighted by several recent experiments, and the experiment at FAIR would add valuable new experimental data in a parameter regime not accessed so far.

1.11 In-situ x-ray diffraction from heavy-ion heated carbon allotropes

In the proposed experiment “In-situ x-ray diffraction from heavy-ion heated carbon allotropes” different forms of carbon (e.g. graphite, diamond) would be heated by irradiation with the heavy-ion pulses. The ionic structure is probed by x-ray diffraction using line emission from the laser-produced hot plasma (e.g. the strong He-alpha resonance line from Fe at an energy of 6.7 keV). Already the first ion beams delivered by the SIS100 to the APPA-cave should enable heating of the samples to temperatures up to 10.000 K, well above the solid-vapor and solid-liquid transition temperatures of carbon. This will be particularly interesting in the regime of non-linear oscillations and the melting transition. Lattice oscillations at these elevated temperatures lead to a decrease in the diffracted intensity, which thus serve as a diagnostic of the lattice temperature or the strength of the inter-ionic potential. The diffraction will also show changes in the lattice constant, structural transitions and melting. Tamping of the heated samples could generate high-pressure conditions transiently crossing the phase boundary to the diamond phase, which would also be detected by the corresponding x-ray diffraction lines. Heating of diamond targets, on the other hand, would allow for in-situ observation of the kinetics of volume diamond-graphitization on the

nanosecond timescale. This will temporarily generate high-density graphite, which then would relax to the ambient density of graphite. Such experiments would be in contrast to ultra-fast heating schemes, such as studied with x-ray free-electron lasers, where graphitization is predicted to happen via a non-thermal phase transition.

9. Laser-Based Plasma Physics (V Bagnoud/M Roth)

There are many laser facilities worldwide that can be used as a driver to reach HED states. However, lasers are not ideally suited to generate uniform and large samples of HED matter. The most interesting and efficient HED platform is located at LLNL, California with the NIF laser that converts the UV energy of the laser into x-rays that can perform uniform heating. Unfortunately, the cost of running NIF is very large and the number of shots available for academic access is limited and in no way capable of fulfilling the demand worldwide.

In contrast, high-peak power lasers in the terawatt to petawatt range are much more widespread [5] worldwide, pushed forward by a wide range of applications from the generation of secondary sources for basic research to industrial applications. This is this aspect of high-power lasers that holds the most application potential at FAIR as diagnostic driver of HED and WDM states. In fact, lasers are the ideal companion of the plasma physics cave at FAIR because they offer flexible and strongly penetrant sources of radiation and particles that will be used as diagnostics for measuring temperature as well as density of the samples heated by FAIR. But they can also be used to probe the structure of materials on the nanoscale using x-ray scattering for instance. Here the plasma physics community for FAIR will leverage the global effort in high-intensity laser development by offering at first a testing ground for new diagnostic concepts like neutron-based temperature measurements of HED for instance, and second deploying the most promising suite of diagnostics to make high-precision diagnostics at FAIR.

1.12 Planned laser infrastructure at FAIR (V. Bagnoud)

The APPA cave will need building a large scale laser in its vicinity in order to generate the kilojoule of energy required to backlight the micro- to mesoscale plasma generated by FAIR. Ideally, this will comprise two beamlines with both nanosecond and femtosecond capabilities allowing running two sets of diagnostics simultaneously for temperature and density measurements for instance. Bringing two kilojoule beams to the APPA cave poses serious radiation safety issues that have been solved by using vacuum image relay telescopes to guide the laser beams to the cave, while additional shielding will be employed near the laser focus to decouple the laser building and APPA cave from a radiation safety stand-point. While everything will be planned in the MSV for the installation of large laser beamlines at FAIR, the funding available in the MSV does not allow for the realization of this project.

In the first phase of FAIR and already for commissioning experiments, a moderate-size laser will be installed that offers sub-nanosecond pulse capability and an energy of 100 J at the second harmonic frequency [6]. This laser will be built in the APPA cave building next to the control room and guided to the target area with a partly image-relayed vacuum beamline. This first laser-based equipment will enable the generation of soft x-rays or planar shocks to be used in combination with the early ion beams of FAIR.

1.13 Laser-based diagnostic sources (x-ray, neutrons) for FAIR (M. Roth/N. Andreev)

The generation of incoherent x-ray radiation with high-intensity laser pulses focused at relativistic intensities has been known for more than three decades now. Although this is an efficient way to create a small (several micrometers) very bright source of radiation, it may not be ideally suited to FAIR because the x-ray source is not directional and must be created

⁵ <http://www.icuil.org/index.php>

⁶ The TDR for the 100 J laser has been approved in 2015.

close to the target. With the size of the samples found in the FAIR target chamber, debris and activation are an issue that prevents bringing expensive pieces of optics close to the target. Fortunately, the field is evolving quickly and the most modern x-ray generation schemes involve the generation of electron bunches that collectively generate x-rays either by betatron radiation or Bremsstrahlung after some propagation. In both cases, the laser can be separated from the target by some meters, greatly simplifying the setup from a radiation and debris mitigation standpoint. These schemes are under development at other facilities worldwide and will become available in the next years. What will be required is to test such generation schemes in the FAIR environment and adapt the laser parameters to them.

Another field for laser-based diagnostics is the generation of neutrons from protons and deuteron beams accelerated with the high-intensity lasers. Here, the plasma physics community involved in FAIR is leading the effort with documented records in laser-generated protons [7] and neutrons [8]. Protons and light ions generated with high-intensity lasers are alone relevant for FAIR physics as they offer a cost effective platform that can be used for testing plasma physics detectors. Such an example can be found in the LIGHT experiment at GSI. Neutrons are even more interesting for FAIR as modern lasers have shown neutrons yields higher than 10^{11} per shot (at the PHELIX facility) that can be employed to make accurate temperature measurements of low-Z material behind a high-Z tamper via neutron resonance spectroscopy. This technique is right now the most promising one for make volumetric temperature measurements on FAIR targets.

10. Discussion Rounds

One the goals of the meeting was to give free time for discussions. The discussion rounds were moderated by several people whose task was to prepare and steer the discussion.

1.14 Discussion Round I: Physics with PRIOR (Varentsov)

The session from Monday on ion beamlines (PRIOR, NDCXII) has been finished by a discussion round about future physics with PRIOR. D. Varentsov answered additional questions about the performance of the PRIOR-II facility at GSI and at FAIR. In particular, the possible repletion rate has been discussed which from the accelerators side can be at 0.5-1 Hz level but may be limited by the radiation protection issues in the experimental area. B. Winkler mentioned that there is a class of very interesting material science experiments where one needs to study semi-static processes with a duration from a few seconds to a minute. This however requires a Hz-level repletion rate of the proton microscope, maybe with a reduced shot intensity.

Several proposal for future dynamic experiments with PRIOR using various drivers were presented and discussed, including material strength and damage studies using a light gas gun (see presentation of A. Zubareva on Tuesday), laser-driven shock wave loading of solids (presentation of M. Roth on Tuesday) and a study of phase transitions in compressed planetary liquids driven by small (30–40 g TNT) high explosive (HE) generators. The Russian collaborators emphasized the importance of high explosive-driven experiments with PRIOR for the community. Such experiments would have especially high discovery potential if large (up to 2 kg TNT) HE generators are used. An experimental protection chamber for such experiments is already available at IPCP and JIHT (Russia), and it can be promptly shipped to Darmstadt for the PRIOR experiments.

1.15 Discussion Round II: Interdisciplinary aspects and LAPLAS (Kühl/Rosmej)

On Tuesday afternoon, the second discussion round took place to address important aspects of the program: the interdisciplinary use of the plasma physics experimental place and the LAPLAS scheme.

⁷ F. Wagner et al. *Phy. Rev. Lett.* **116**, 205002 (2016)

⁸ M. Roth et al. *Phy. Rev. Lett.* **110**, 044802 (2013)

1.15.1 Interdisciplinary Experiments

The experimental capability prepared in the APPA cave around the plasma physics beam line should be made available to a broader community because plasma physics studies are not the only possible use of this experimental place. In particular, a strong interest to add interdisciplinary research to the agenda was expressed by several researchers during the workshop. This includes in particular material research, nuclear physics and biophysics. These subjects are by themselves part of the FAIR programs APPA and NUSTAR, but here a strong motivation was expressed to use the planned experimental facilities of the plasma physics installations for unique interdisciplinary research.

As explained in contributions by M. Tomut (GSI/FAIR), Doeppner (LLNL, USA), T. Schenkel (LBL/ATAP, USA), and B. Winkler (Goethe University, Frankfurt), material science experiments will benefit tremendously by using the novel diagnostic schemes given by Proton Radiography as well as the laser driven schemes proposed at the plasma physics installation in combination with advanced experimental schemes for the preparation of particular states of matter available at other institutes. Another exciting aspect will also be to add the interaction with the heavy-ion beam.

In the combination the authors expect to touch a new regime of physics, adding unique new capability to FAIR. The requirements are:

- Proton radiography with $\sim 10^{11}$ protons per bunch
- Laser driven diagnostics

Another strong new physics sector can be reached by using the capability to produce radioactive isotopes and isomeric states with the accelerator and injecting into a plasma target driven by a laser exceeding 300 J. This was the summary of the contributions by Zhu (MPI Heidelberg), V. Tikhonchuk (CELIA Bordeaux), C. Kozhuharov (GSI), J. Litvinov (GSI), A. Yakushev (GSI) and T. Doeppner (LLNL). From theoretical prediction, and using experimental techniques established by the contributors, the plasma physics installations at FAIR will enable studies of nuclear excitation by electron capture or atomic excitation in a laser driven plasma. This will be due to the combination of the heavy-ion beam, the parameters in the plasma, and dedicated nuclear diagnostics. The requirements are:

- Heavy-ion beam with $> 10^{10}$ ions or protons per bunch
- Plasma target driven by a laser exceeding 300 J on target.

Last but not least, the field of biophysics will find additional opportunities. Direct use for biophysics diagnostics and development of novel treatment schemes is part of the program of the proton radiography installation and was discussed separately. Combination with the laser installations within the APPA cave has a strong potential to expand these activities even further, including also laser driven proton acceleration. This was expressed in contributions by M. Prall (GSI) and G. Kraft (GSI & TU Darmstadt). For such developments in addition to the requirements of the proton radiography an ultra-intense laser source will be needed:

- Proton radiography with $\sim 10^{11}$ protons per bunch
- Laser exceeding 10^{19} Watt/cm².

1.15.2 Compression experiments with hollow and circular heavy ion beams: the LAPLAS scheme.

Low entropy compression of matter (frozen hydrogen, water) enclosed in a heavy temper heated by high intensity U-ion beams was proposed by N. Tahir in collaboration with IPCP, Chenogolovka in [9,10,11,12]. Simulations show that multiple shocks induced in the LAPLAS - scheme lead to generation of matter states close to those of giant planet. In this scheme a pressure up to 15-30 Mbar and up to 30 fold compression of the hydrogen are expected. At

⁹ N. A. Tahir et al. Phys. Rev. E 63 016402 (2001)

¹⁰ N.A. Tahir et al. High Energy Density Phys. 2 21 (2006)

¹¹ N. A. Tahir et al. New Journal of Physics 12 073022 (2010)

¹² O. Rosmej et al. Phys. Rev. A 72, 052901 (2005)

high U-beam intensity of $5 \cdot 10^{11}$ ions and energy deposition time of 100 ns metallization of hydrogen and exotic ionic states of water can be reached.

The wobbler system, developed at the ITEP, Russia [13], provides high quality hollow beams rotating with a frequency of 325 MHz. This high frequency ensures homogeneous heating of the cylindrical tamper and high symmetry of matter compression. Influence of the ion beam heterogeneities on the compression symmetry and final parameters of reached matter states has been studied using two different hydrodynamic codes [14,15] and presented during the workshop by D. Lyakin, ITEP, and A. Shutov, IPCP. In both cases, high stability of the cylindrical compression to the deviation of the hollow ion beam from the ring-form caused by chromatic aberrations of the ion beam optics, mismatching of the ion beam positioning (up to 25-50 μm) and to the sinus-like inhomogeneity in the ion energy deposition within 5% were demonstrated. Full-scale ion optic model was used to reproduce a realistic 3D energy deposition in the target volume to be used in 2D and 3D hydrodynamic simulations. Therefore, one can state that the LAPLAS scheme continues to be an important part of plasma physics program at FAIR.

Simulations of the compression dynamics made for U-beam parameters during the start phase of the SIS100 and using hollow and circular shapes of the ion beam show very promising physics by applications of LAPLAS and Mach schemes [15], where matter compressed up to tens-hundreds of GPa reaches interesting for EOS-research phase states. These schemes can also be used to study the growth of the Richtmyer-Meshkov instability in the linear and the non-linear regimes by applying an initial corrugation at the materials interface. Therefore, compression experiments using hollow and circular U-beams have high scientific potential during the SIS100 start version (Day-one experiments) and by SIS100 full performance.

Diagnostic of compressed matter states, placed in mm-long and tens of micrometers in diameter channel is still under discussion. O. Rosmej has proposed to use for these purposes X-ray fluorescence of the target material or/and heavy ions [12] as well as time resolved measurements of the ion beam energy distribution of the primary and secondary (probe) beams penetrating compressed matter. First experiments on x-ray fluorescence with Au-beam showed promising results.

At the same time, proton radiography [16] continues to be a unique tool for measurements of the density distribution in the LAPLAS experiments with microns spatial and tens of nanoseconds time resolutions and requires an additional beam-line perpendicular to the SIS100.

1.16 Discussion Round III: Isochoric Heating Capabilities at FAIR (Neumayer)

On Wednesday morning, an open discussion was held to address the technique of directly heating targets by irradiation with the intense heavy ion that will be delivered by the FAIR accelerator. This is a very straight forward approach in that the heavy ions are bunched to a pulse of 100 nanoseconds (or below), and focused by the magnetic focusing system in the APPA cave to spot sizes of order 1mm onto the target. The stopping length of the energetic ions (0.2...2 GeV/u) in matter at solid density is millimeters or even centimeters. This provides the worldwide unique capability to volumetrically heat samples of macroscopic dimensions to reach high energy density (HED) conditions.

As was pointed out and stressed by one of the key speakers (D. Riley/U. Belfast) this allows to produce plasmas in the challenging warm-dense matter regime without having an extremely hot (keV) plasma right next to it, as it is usually the case when employing laser-driven shocks, one of the most common approaches to generate HED plasmas in the laboratory. This makes

¹³ The TDR for the wobbler is available from the technical coordinator of the plasma physics collaboration

¹⁴ <https://www.comsol.com>

¹⁵ N. A. Tahir et al. EPS contributions (2011)

¹⁶ D. Varentsov et al. Review of Scientific Instruments 87, 023303 (2016)

accurate characterization of the plasma often very challenging, if not impossible. Even more severe, the intense x-ray emission of such an extremely hot plasma, as well as supra-thermal electrons produced in the intense laser-plasma interaction can cause a significant amount of preheat in the sample, strongly altering the initial conditions, which can be a substantial impediment when trying to use experimental results to benchmark hydrodynamic codes or test dense matter theory.

Heavy ion heating is also in many ways complementary to the volumetric heating capabilities provided e.g. by the hard x-ray free-electron lasers that recently went into operation (LCLS/Stanford, SACLA/RIKEN) or will be commissioned in the next years (European XFEL, LCLS-2). For example, while still being fast enough to ensure quasi-isochoric heating, the timescale of tens of nanoseconds provides for matter states at conditions close to thermal equilibrium. Also, the long timescales together with the large size of the samples strongly relax requirements to the diagnostics. Finally, while isochoric heating with keV x-rays is limited to rather low-Z elements, the range of energetic heavy ions allows use of virtually any target material.

Energy deposition of the heavy ions in the target can be accurately calculated and promising new techniques for online monitoring by measuring characteristic line emission of both target and ion beam are being developed (O. Rosmej/GSI).

Already ion pulses expected from the SIS18 once it is upgraded to the parameters required to inject into the SIS100, will deliver $3...4 \times 10^{10}$ ions per bunch. These will yield specific energy deposition of order 10 kJ/g, and heat targets to temperatures around 1eV, well above the critical temperatures of many metals. First beams from the SIS100 synchrotron with pulses exceeding 10^{11} ions will deposit tens of kJ/g, reaching temperatures of several electron-volt, accessing the strongly coupled plasma regime. When FAIR in the MSV will run at the full projected performance, 5×10^{11} ions will produce samples with more than 100kJ/g specific energy, corresponding to temperatures above 10eV.

As had been detailed in several talks during the workshop in sessions dedicated to this novel and unique scheme (I. Lomonosov/IPCP, I. Iosilevsky/JIHT, V. Mintsev/IPCP), interesting and exotic phases of matter can be produced at unprecedented quality. These include the two-phase liquid-gas regime, the region around the critical point, and the regime of strongly coupled, non-ideal plasmas. It was pointed out, that the critical point location for most materials still remains unknown. Theoretical predictions often vary by 100% or more, and experiments are hampered by the difficulty to produce matter at the required high-temperature conditions in a well-controlled manner. The parameter range accessed with the heavy-ion heating technique also will allow the study of exotic phase transition, such as a possible plasma phase transition, metal-to-insulator transition, non-congruent phase transitions or abnormal thermodynamics near entropic phase transitions. All these represent highly interesting fundamental physics problems, but are also relevant to earth and planetary science, as well as technical applications.

Diagnostics for a prototypical heavy-ion heating and expansion experiment will comprise a set of sophisticated optical techniques, such as pyrometry (surface temperature), interferometry and shadowgraphy (surface and expansion velocity), all with high spatial and temporal resolution. Prototypes of such diagnostic setups have already been tested successfully in experiments at GSI's HHT-cave on samples irradiated with few 10^9 ions per pulse. The community strongly advocated to already take up experimental activities at the HHT-cave, as soon as the upgraded SIS18 will be in operation. This will be crucial to commission, test, and improve experimental schemes and diagnostics envisaged for the plasma physics program at the APPA cave. Given the record high intensities recently demonstrated for the SIS18, it can be expected that this will already result in highly visible novel experimental results in the field of HED research.

The heavy-ion heated targets undergo both during the heavy-ion heating as well as in the isentropic expansion phase, a significant hydrodynamic evolution, with densities ranging

from solid to less than $1/10^{\text{th}}$ of solid. This is precisely the warm-dense matter regime, where equation-of-state is very uncertain. There was broad consensus that a direct density measurement as facilitated by radiographic imaging with a laser-driven hard x-ray backlighter would truly benefit the scheme and enhance the quality of the obtained data.

Also, it was pointed out that such a high-energy short-pulse laser based diagnostics capabilities would significantly increase the scientific discovery potential of the plasma physics installation at FAIR, as it would enable many state-of-the-art x-ray diagnostic techniques, such as x-ray diffraction, absorption spectroscopy, or x-ray Thomson scattering.

APPENDIX 1 - List of Posters

Poster session: Monday, July 11th, 2016, 15:30 – 16:50 in the Foyer of the KBW building

Participant	Poster
ANANYEV, Sergey	Determination of the Parameters of the Hot Plasma Formed during the Implosion of Wire Arrays from Time Resolved X-ray Spectra of H- and He-like Ions
BRABETZ, Christian	Pre-amplifier upgrade and beam quality control at PHELIX
CAO, Leifeng	Recent progress of x-ray single-order diffraction grating for plasma diagnostic
CHIGVINTSEV, Alexander	Anomalous isostructural crystal-crystal and crystal-fluid phase transitions in modified Coulomb model
DEUTSCH, Claude	Two-body and three-body mesonic bound states in WDM target plasmas
EFREMOV, Vladimir	Hydrodynamics of silicon dioxide destruction under laser action
ENDRES, Michael	A light-gas driver for studies on dynamic matter properties with PRIOR
GOPAL, Amrutha	Ultra-strong magnetic field generation during high-power laser solid interaction
GUNST, Johannes	Mo isomer triggering with the XFEL - direct and plasma-mediated channels
GURLUI, Silviu	Space-and-time-resolved spectroscopy of transitory laser ablation plasma
HORNUNG, Johannes	Development of a FROG for time-resolved characterization of relativistic laser-plasma interactions
KALAL, Milan	New Features in Complex Interferometry Diagnostics
KANTSYREV, Alexej	High-energy proton microscopy for investigation of extreme state of matter
KHISHCHENKO, Konstantin	On possible investigations of thermodynamic properties and phase transformations of materials at FAIR
KOTZIAS, Bernhard	Fragmentation of Hydrogen - LASER Experiment
MEISTER, Claudia-Veronika	1. Influence of the ion structure on force-force correlation functions of warm dense matter 2. Magnetohydrodynamic formulae for density, pressure, velocity, and magnetic field jumps in a perpendicular shock wave of an ideal plasma

MOCHALOVA, Valentina	Experimental investigation of shock wave compression of heterogeneous anisotropic materials for experiments at PRIOR
POPOV, Vyacheslev	Self-injection and laser wakefield acceleration of electrons in aluminum plasma with the processes of optical field ionization
RÖPKE, Gerd	1. Plasma Spectral Line Profile in an Open Quantum System Approach 2. Transport Properties of Warm Dense Matter: T Matrix Effects
SCHÖNLEIN, Andreas	Generation of Warm Dense matter by Isochoric Heating of a Ti-wire
SHILKIN, Nikolay	Target chambers for high energy density and high explosive experiments
SHUTKO, Yulia	Beam Induced Fluorescence (BIF) Profile Monitor Development for High Current Heavy Ion Beam
STROEV, Nikita	Non-congruent phase transition in modified Coulomb model of the binary ionic mixture
SUGITA, Kei	Alternative High Field sc Magnets for a Final Focusing System with Large Aperture High Gradient Quadrupoles
WAGNER, Florian	Optimizing laser driven ion sources for applications at FAIR
WIECHULA, Jörg	Construction, characterization and optimization of a plasma window based on a cascade arc design for FAIR
WU, Dong	Monte-Carlo approach to calculate the ionization of warm dense matter within particle-in-cell simulations
WU, Yuanbin,	Nuclear reactions of astrophysical interest in laser plasmas
ZHAO, Yongtao	Energy loss and wakefield modulacation of ion beam in plasma

APPENDIX 2 - List of Participants

Dr. AFEYAN, Bedros
Dr. ANANYEV, Sergey
Prof. ANDREEV, Nikolay E.
Dr. BAGNOUD, Vincent
Prof. BASHIR, Shazia
Prof. BATANI, Dimitri
Prof. BAUCHIRE, Jean-Marc
Dr. BLAZEVIC, Abel
Prof. BOINE-FRANKENHEIM, Oliver
Prof. BONITZ, Michael
Mr. BORM, Björn
Dr. BORNEIS, Stefan
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