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ABSTRACT

The Facility for Antiproton and Ion Research (FAIR) will employ the World's highest intensity relativistic beams of heavy nuclei to uniquely create and investigate macroscopic (millimeter-sized) quantities of highly energetic and dense states of matter. Four principal themes of research have been identified: properties of materials driven to extreme conditions of pressure and temperature, shocked matter and material equation of state, basic properties of strongly coupled plasma and warm dense matter, and nuclear photonics with a focus on the excitation of nuclear processes in plasmas, laser-driven particle acceleration, and neutron production. The research program, principally driven by an international collaboration of scientists, called the HED@FAIR collaboration, will evolve over the next decade as the FAIR project completes and experimental capabilities develop. The first programmatic research element, called "FAIR Phase 0, officially began in 2018 to test components, detectors, and experimental techniques. Phase-0 research employs the existing and enhanced infrastructure of the GSI Helmholtzzentrum für Schwerionenforschung (GSI) heavy-ion synchrotron coupled with the PHELIX high-energy, high-intensity laser. The "FAIR Day one" experimental program, presently scheduled to begin in 2025, commences the use of FAIR's heavy-ion synchrotron, coupled to new experimental and diagnostic infrastructure, to realize the envisaged high-energy-density-science research program.

I. INTRODUCTION

Matter at extreme conditions of temperature and pressure, often denoted as high energy density (HED) matter, occurs widely in the universe, making up most of the matter condensed in compact astrophysical objects such as stars, brown dwarfs, and planetary interiors.[1] The properties and behavior of HED matter also underpin the performance of intense laser–matter interactions,[2] inertial confinement fusion (ICF),[3,4] shock-driven high-entropy material states,[5] or, in general, the behavior of any matter with an energy density exceeding 10 to 100 kJ/cm^3 (see Refs. 6 and 7 and references therein). Developing experimentally validated models of HED matter, with the goal of revealing its structure and properties, is a principal goal of ongoing HED physics research worldwide. Such properties include the equation-of-state (EOS), phase boundaries, critical points, optical and electrical properties, and hydrodynamic and magnetohydrodynamic properties.

Within this field, there is significant interest in understanding giant planetary interiors, where pressures range from 1 to 100 Mbar, densities from solid density up to several times of solid density, and temperatures from 1 to 10 eV. Matter at these conditions is typically referred to as warm dense matter (WDM). It is essential to understand the fundamental thermodynamic properties of WDM for solving, for example, questions of planetary formation, evolution, and structures. For this reason, significant worldwide research is under way to both understand the properties of WDM in planet interior conditions, like those of metalized hydrogen,[8,9] and to answer more fundamental questions related to the close-range particle interactions in WDM.[10,11] This research includes a substantial effort in modeling and theory.[12–14]

Within this context, understanding WDM is a grand plasma physics challenge.[6] This plasma regime is challenging because the thermodynamic properties cannot be understood in terms of small perturbative expansions from ideal plasma models. The potential interaction energy, E_p, between the plasma constituents (ions and electrons) is comparable to the thermal energy, E_k, the interaction potentials are long-ranged, and the system is strongly coupled. The usual classical plasma closure techniques, where the Coulomb coupling parameter $\Gamma = E_p/E_k$ is small, are not applicable. In addition, the de Broglie wavelength of the electrons is comparable to the inter-particle distance (electron degeneracy parameter $\Theta \approx, 1$), necessitating a quantum mechanical description. Hence, WDM does not fall neatly within the parameter space typical of either ordinary condensed-matter physics or classical plasma regimes where Coulomb shielding mitigates the long-range ionic interactions.

A. Existing high energy density facilities

Experimental investigation of HED matter, with a view to model development and validation, is a rapidly growing scientific endeavor. A variety of experimental approaches are employed to create the desired states of HED matter with various advantages and constraints.

Quasi-static experimental techniques, using diamond anvil cells and laser-heated diamond anvil cells, paired with synchrotron-based x-ray diffraction, can access modest pressures and temperatures (up to 3.8 Mbar at 5700 K)[15] in cubic-micrometer-sized volumes for material structure and EOS studies. As an example, Anzellini *et al.* have measured the melt temperature of iron up to a pressure of 2 Mbar (approximately two-thirds of the predicted pressure for the Earth's inner-core boundary[16]). Higher static pressures, using micro ball nano-diamond anvils with 60-nm samples, can reach pressures of up to 6 Mbar.[17] However, the small sample size makes diagnosis difficult when using the available brightness of synchrotron x-ray sources. Furthermore, reaching WDM-relevant temperatures under such conditions remains a challenge.

As an alternative to quasi-static compression, laser-driven shock compression techniques, with intensities exceeding 10^{13} W/cm^2, have been used since the 1970s to explore the EOS of materials along the Hugoniot. However, the requirement for high-quality measurements imposes additional energy and 1D spatial uniformity constraints. Large laser facilities, such as the National Ignition Facility (NIF) or the Omega laser in the USA, can create pressure conditions exceeding one gigabar[18] and relevant to the interior of giant exoplanets[19] and stars. Recently, such facilities have been successfully used to differentiate between EOS models.[20] For example, they were able to create superionic water ice and measure the melt temperature of diamond[21] under ultra-high pressure conditions.

Figure 1 shows that laser-driven techniques can access an area of the HED physics space much hotter than what is accessible by diamond anvil cells. Laser-driven techniques are highly relevant to understanding the stellar structure, stellar dynamics, and ICF.[3] Ramp compression is another laser-based technique that is more appropriate to WDM studies above 10 Mbar and at lower temperature.[22,23] However, these techniques exhibit features associated with the transient nature of the laser-matter interaction. In particular, samples are driven to HED and WDM states within nanoseconds and with very high strain rates. This aspect is not depicted in Fig. 1 but should be kept in mind, as it adds another dimension to the two-dimensional plot of high relevance for material research under extreme conditions. These drive conditions control the temperature-density compression path and influence both phase transitions and final material states.

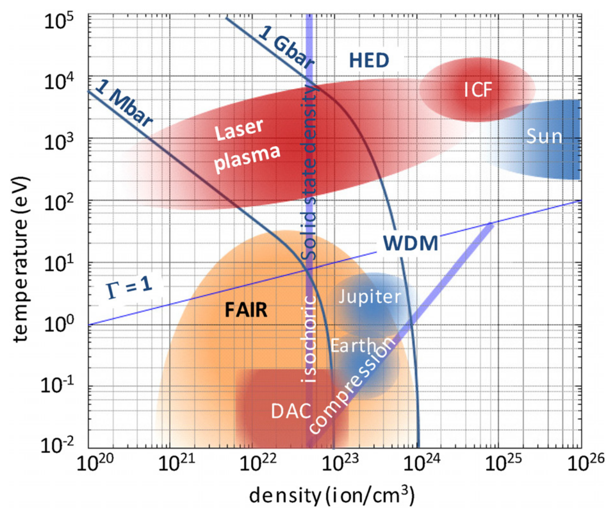


FIG. 1. Density-temperature diagram showing HED states achievable at FAIR, their relevance to planetary physics applications, and complementarity with other drivers like diamond anvil cells (DAC). The techniques discussed below offer great flexibility to access a wide range of WDM states by techniques ranging from isochoric heating to shock heating along Hugoniots to quasi-adiabatic or low-entropy compression.

Fourth-generation light sources, based on free electron lasers (FELs),[24,25] use coherent x-rays to create or probe HED matter and are the latest addition to the family of HED drivers and facilities. Facilities, such as the linac coherent light source (LCLS) and the European x-ray free-electron laser, possess novel pump-probe capabilities to generate and study material properties under HED matter or WDM conditions.[26] The ultra-high-brilliance of these sources enables the use of unique probe techniques with coherent visible and infrared light, such as saturable absorption.[27] In addition, ultra-bright and coherent x-ray radiation is dramatically improving the resolution of x-ray based diagnostics and methods. High-precision, low-background measurements on WDM have been demonstrated using coherent x-ray scattering.[5] Coherent x-ray diffraction is capable of time-resolved measurements of phase transitions and their dynamics like, for example, in carbon[28,29] or polyethylene[30] under pressure conditions relevant to the giant planets.

While x-ray free-electron lasers (FELs) are unique and exquisite experimental tools for HED studies, they generate states of matter, using laser-driven shocks or the FEL itself, which are typically transient and not in thermodynamic equilibrium. Homogeneous, long-lived WDM and HED matter states, in local thermodynamic equilibrium, have been generated with slower shocks driven by high explosives, two-stage light gas guns, or Z-pinch-driven flier plates.[31] High explosives and staged gas guns can drive centimeter-scale material samples up to megabar pressures (100 Mbar for explosions) and temperatures of approximately one to several electron volts.[32–35] However, shock-driven states are constrained to the Hugoniot.

There exist many physical conditions where the states lie closer to the isentrope than the Hugoniot. Over the past two decades, the Z Accelerator at the Sandia National Laboratory has pioneered the use of pulsed-power to drive quasi-isentropic compression in millimeter-scaled targets over 120 ns using magnetic pressure.[36,37] This technique has demonstrated pressures of over 1 Mbar and has been used to study the polymorphic phase changes in multiple materials.[38] A large sample size and relatively long compression times make the Z machine an excellent platform for material EOS studies. Nevertheless, the Z machine is, in the final analysis, limited in the number of materials that can be investigated by its shot data rate. As noted below, Facility for Antiproton and Ion Research (FAIR) will significantly augment the capability to isentropically compress large samples to multi-megabar pressures with a view to understanding material EOS at high-pressure.

B. Modeling and diagnostic tools

Modeling HED matter and WDM is challenging; it is a rapidly developing field that requires experimental data for bench-marking purposes. In the lower temperature range of this domain, the electron-ion interaction potential becomes comparable to the electron kinetic energy, the ions are partly ionized, and the ionic binding energy is a significant fraction of the total internal energy. Free electron density depends on the average ion charge state, and hence, plasma transport properties are strongly affected by atomic bound-bound and bound-free transitions. In addition, when the electron thermal wavelength becomes comparable to the average electron–electron distance, the free electrons must be treated quantum-statistically.

When the average ion kinetic energy becomes comparable to the Coulomb energy, the ions become strongly coupled, and ion–ion interactions can no longer be treated as small perturbations. The plasma internal energy and static ionic structure can be efficiently calculated using integral equations or by molecular dynamic simulations assuming an electron-ion interaction potential.

The Thomas–Fermi (TF) method is often employed to model material EOS. In this method, a self-consistent solution is sought for the potential of an ion surrounded by free electrons that obey Fermi-statistics. The TF method accounts for average ionization, ionization potential depression (IPD), and the effects of Fermi pressure. However, effects of the discrete atomic structure are absent in the TF-description. This becomes particularly visible at extreme pressures, when K-shell ionization becomes appreciable. Atomic structure effects can be treated by average atom models,[39] where the Schrödinger equation is solved in a self-consistent potential bounded by a sphere around the ion. Recently, this method has proven to deliver reliable predictions confirmed by experimental data along the Hugoniot in shock experiments.[40,41] However, as the system approaches the (cold) solid-state regime, a solid-state physics description is required, and models such as the Mie-Grüneisen EOS or the Debye model are applicable.

EOS and material properties are tabulated over a wide range of conditions and the results are stored in a database that can be efficiently utilized by hydrodynamic codes. These databases, like SESAME, that is maintained by the Los Alamos National Laboratory,[42] and the database maintained by the Joint Institute for High Temperatures RAS in Moscow and the Institute of Problems of Chemical Physics RAS in Chernogolovka,[43] employ interpolative and predictive theoretical models that are benchmarked against experimental results. Nevertheless, there remains an exigent need for experimental data for improved database accuracy.

Accurate diagnosis of HED matter is also a challenge. Limitations on drive energy for creating HED conditions results in small sample volumes, typically of order 10^{-3} to $1\,\mathrm{mm}^3$. Concomitant hydrodynamic timescales are in the nanosecond range. Thus, high spatial and temporal resolution is a requirement for diagnostics. For cases where the sample surface is optically visible, optical diagnostic techniques are viable. In temporally streaked optical pyrometric measurements, the sample surface temperature is inferred from the thermal emission. Interferometric techniques allow for high-precision measurements of surface velocities[44] that inform EOS models or determine stress–density relations.[9,22] Measuring optical reflectivity also provides estimates of electronic conductivity that is indicative of, for example, the conjectured superionic water phase[21] or a possible insulator-metal transition in dense deuterium.[9]

HED states are, in general, opaque, and thus, optical probing is limited to the sample surface. Volumetric measurements require penetrating radiation, such as energetic x-rays, charged particles, or neutrons. For example, x-ray backlighting, based on the emission of highly ionized mid-Z plasmas (up to 10 keV), is an established ICF technique to assess implosion symmetry and to measure the imploding shell mass and velocity.[45] X-ray radiography also enables absolute EOS measurements on indirectly driven convergent shocks up to very high pressures.[20]

Thermal x-ray emission from hot plasmas, produced by energetic laser pulses at intensities of order 10^{15} W/cm^2, becomes increasingly inefficient for photon energies above 10 keV.[46] Higher-energy photons can be produced by the supra-thermal electrons in relativistic laser–matter interactions at intensities exceeding 10^{17} W/cm^2. For this reason, many major HED facilities possess high-energy short-pulse laser capabilities, like the Z-PW,[47] Omega-EP,[48] or PETAL,[49] to enable hard x-ray backlighting of samples at high densities, such as during the stagnation phase of ICF implosions. Besides measuring mass densities and imaging hydrodynamic evolution, x-ray backlighting also provides information on the microscopic structure by using scattered or diffracted beams with appropriate spatial coherence. Here, one should mention x-ray Thomson scattering[50] that not only delivers information on additional macroscopic measurables such as temperature and ionization but also gives precise information on collisions and quantum effects at the microscopic level. Complementary information on temperature can be inferred from spectrally resolved transmission measurements near the sharp K-edge transition, using the so-called x-ray absorption spectroscopy (XANES) technique.[51] The advent of x-ray FELs, with unique properties such as brilliance, coherence, bandwidth, pulse duration, and focusability, drives the development of these coherent x-ray techniques even further for diagnosing micrometer-scale samples on femtosecond timescales.

In summary, the scientific HED-physics community has developed a versatile suite of modeling and diagnostic techniques and tools to advance this developing field of scientific research. These techniques and tools are widely applicable to the international ensemble of existing and upcoming HED drivers for elucidating the structure and properties of HED matter.

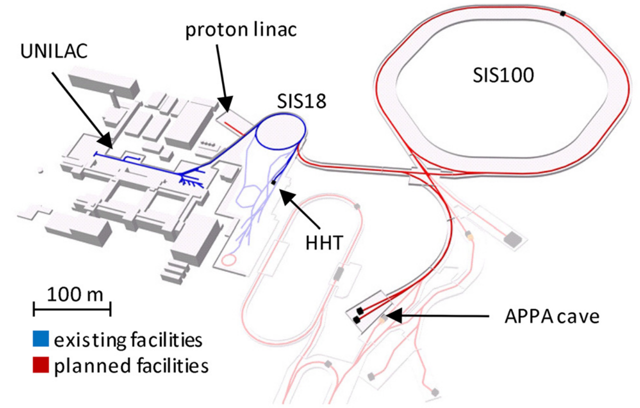
C. HED research at FAIR

The Facility for Antiproton and Ion Research (FAIR), currently under construction in Darmstadt Germany, will explore the use of intense, heavy-ion beams (up to 5×10^{11} uranium ions per pulse) for creating high-energy-density states of matter. As shown in Fig. 2, FAIR is composed of the existing accelerator infrastructure of the GSI Helmholtzzentrum für Schwerionenforschung (GSI) and the new SIS-100 superconducting heavy-ion synchrotron[52] along with new experimental areas like the atomic and plasma physics application (APPA) cave. In total, FAIR will offer worldwide unique and complementary opportunities for high-energy-density scientific research.

The interaction of highly charged, heavy-ion beams with matter, coupled with a range of target configurations (discussed below), enables the ability to create millimeter-scale macroscopic quantities of HED matter or WDM that are spatially uniform and for timescales equal to the beam-target interaction time (of order 100 ns). These irradiation times are long compared to thermodynamic timescales of interest and therefore allow the HED matter to achieve quasi-steady-state conditions.

Energy deposition simulations, using the SRIM code,[53] predict that intense pulses of uranium 28+ ions, focused to millimeter-squared areas, can deposit energy densities in the range of 50 to 300 kJ/g, depending on the required deposition uniformity. Energy deposition time-scales of order 100 ns ensures attainment of equilibrium conditions, while ion beam stopping ranges of order centimeters enable homogeneous energy deposition in relatively large samples with concomitantly small gradients.

Figure 1 illustrates the HED states achievable at FAIR for a set of different target configuration schemes and beam irradiation conditions based on energy deposition and hydrodynamic simulations. At present, three target schemes are envisaged for FAIR HED experiments as discussed below: heavy ion heating and expansion (HIHEX),[55]



	Current performance		FAIR	
	Protons	U^{73+}	Protons	U^{28+}
Max. energy (GeV/u)	4.7	1	10	2.7
Particles/bunch	1×10^{10}	1×10^{10}	2.5×10^{13}	5×10^{11}

FIG. 2. A schematic view of the present accelerator facility at GSI (blue) and the FAIR (red). The HED-physics research facilities include the SIS-18 and SIS-100 synchrotrons, the high-energy high-intensity PHELIX laser, and dedicated experimental caves. The table shows the main synchrotron parameters. Until the start of the FAIR accelerator, experiments will utilize the upgraded SIS-18 beams at GSI. The first experiments using the FAIR accelerator will utilize the SIS-100 beams in the APPA Cave starting in 2025.

laboratory planetary sciences (LAPLAS),[56] and the stimulated Mach configuration.[57]

The HIHEX scheme is designed to allow beam-irradiated matter to isochorically and uniformly heat while being spatially confined by tampers. This scheme has already been tested at GSI, although with uranium beam intensities below 10^{10} ion/pulse.[58] During these early experiments,[59] temperatures up to 5000 K were observed using 4×10^9 uranium ions at 350 MeV/u, when the beam is focused to 300 μm. In HIHEX experiments, the ion beam directly heats the sample under investigation, as shown on the left-hand side of Fig. 3. Energy deposition up to 100 kJ/g results in Mbar pressures and eV temperatures. To minimize target expansion during heating, tampers consisting of different materials that are transparent either in the visible (i.e., LiF or Sapphire window) or in the x-ray regime (e.g., BN or B4C) surround the sample. In this way, high-entropy plasma states, over a wide parameter range in temperature and density phase space, can be accessed.[60]

Modified HIHEX schemes have been explored where the expansion is completely suppressed by surrounding the sample material with a tamper that will be heated by the ion beams as well, thus generating a net-inwards pressure.[61] Heating of thin foils has also been suggested as a means to drive an isothermally expanding sample and provide the potential for opacity measurements in the vacuum ultraviolet (VUV) and soft x-ray spectral regions.[62]

The HIHEX experimental platform is intended to provide new experimental information about critical points and two-phase gas-liquid boundaries of many materials heretofore not explored by other

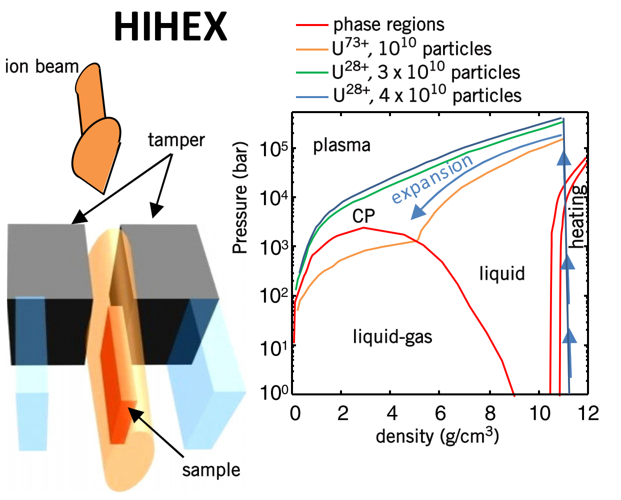


FIG. 3. The HIHEX scheme where ion beams (U^{28+} or U^{73+}) heat a material sample confined between two tampers. The sample heats isochorically with subsequent isentropic expansion. Using the SIS-100 parameters envisaged for FAIR Day-one experiments, the HIHEX scheme will be able to fully explore the critical points of many periodic system metals. Right-hand side: HIHEX predictions for lead for various ion-beam intensities.[54]

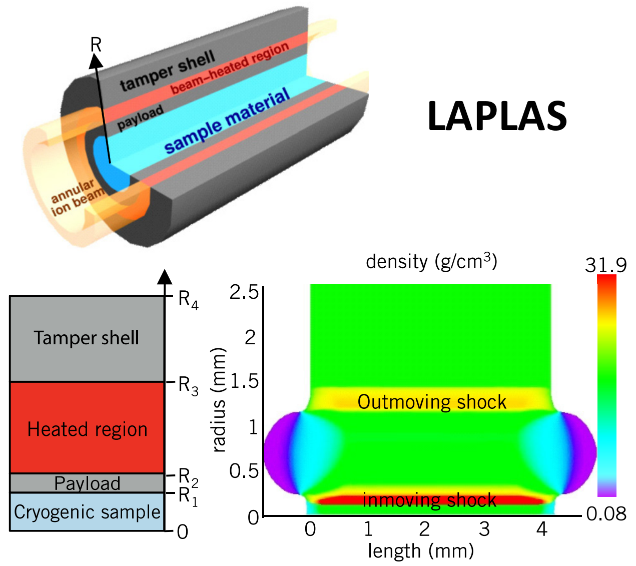


FIG. 4. The LAPLAS scheme uses annular heavy ion beams (U^{28+}) to heat a material driver inside a cylindrical tamper shell. Subsequent material heating drives a cylindrical compression of the sample material. Relatively uniform HED matter can be formed and probed with this technique up to Mbar pressures. The example shown above[70] is a simulation of an iron sample compressed by a tungsten shell up to a density of 18 g/cm^3, temperature of 1260 K, and pressure of 7.6 Mbar using a 1.5-GeV/u uranium beam from the SIS-100 with a 75 ns bunch of 5×10^{11} ions.

techniques. This is depicted by the arrows in the diagram on the right hand side of Fig. 3 that shows predictions on the phase diagram of lead.[54] In this way, HIHEX offers a complementary approach to other drivers to study WDM off the Hugoniot.

For measurements requiring compressed matter at high pressures and lower temperatures, like those found in the interior of giant planets, the LAPLAS scheme will be employed. In LAPLAS, a cylindrical sample is surrounded by a high-Z tamper. A beam-wobbler module induces a fast rotation of the ion beam in the focal plane, effectively generating a ring-shaped focus.[63] This allows energy deposition into the tamper cylinder with minimal heating of the sample material in the center (Fig. 4). Simulations show that the expansion of the heated tamper will result in a cylindrically symmetric and uniform inward compression, with near-isentropic compression of the sample material. Implosion or compression stability is provided by the elasticity and plasticity of the metallic tamper shell where elasticity determines the shell stability and plasticity determines the degree of symmetry that must be provided by the wobbler heating system.[64,65]

Simulations show that the HED conditions achievable with LAPLAS are comparable to the interior of planets. For example, computational studies[66] predict that, with this scheme, superionic water can be generated. Superionic water is expected to be prevalent inside the ice giants Uranus and Neptune.[67–69] Moreover, it will be possible to study the chemical effects of other elements that are abundant in the interior of icy giant planets such as carbon-hydrogen phase separation.[29] Simulations also predict that iron, at conditions similar to the Earth's core and those expected in "super-Earths," can be produced with the LAPLAS scheme.[70,71]

Compared to other compression methods, LAPLAS offers advantages like a slow compression time of several tens to hundreds of nanoseconds and the absence of Rayleigh-Taylor instabilities during the compression phase. However, the highest risk associated with LAPLAS derives from the necessity to control the cylindrical symmetry in the energy deposition to the percent level. In addition, measurement of the sample properties through the tamper is difficult, although on-axis measurements, based on radiography and spectroscopy, are technically feasible.[70]

The third experimental scheme under investigation is the stimulated Mach configuration[57] that enables generating planar shocks to study hydrodynamic instabilities, material properties, and phase mixing. Unlike the HIHEX or LAPLAS schemes, where ions travel through the target, the stimulated Mach scheme exploits the Bragg peak such that the heavy ion beam is fully stopped in a dense cone that hosts a cylinder of the sample material. As illustrated in Fig. 5, the localized energy deposition around the Bragg peak and the special conical shape of the target generate a planar shock front. This shock subsequently propagates in the forward direction into the target material. When using a FAIR ion beam pulse with 5×10^{10} uranium ions, the temperature in the sample material remains below the melting temperature, while the pressure remains below 1 Mbar. The material, therefore, remains in the solid phase and thus allows studies of hydrodynamic instabilities in solid materials. With the full FAIR intensity of 5×10^{11} uranium ions, simulations predict that the sample material is liquefied, and thus, one can study the hydrodynamic instabilities in fluids. The Mach configuration makes use of the energy deposition from the sharp Bragg peak. This energy deposition can be modified by fission or fragmentation of the projectile ions, resulting in lower shock pressures and lower temperatures. Nevertheless, simulations show that shock-driven instability studies can be carried out over a wide range of pressures. The Mach configuration also produces significant amounts of activated debris, and radiation-protection considerations can ultimately limit the experimental repetition rate.

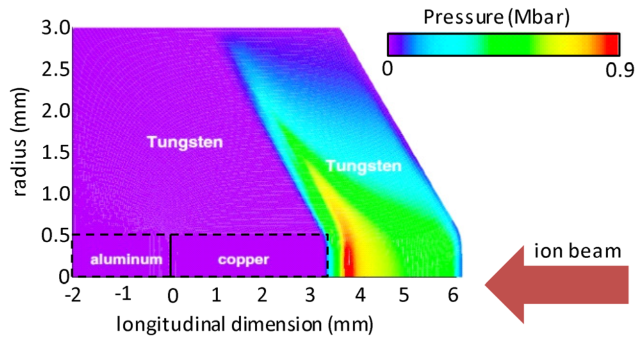


FIG. 5. Pressure distribution in a stimulated Mach configuration target at the time of the irradiation (5×10^{10} uranium ions focused to a 2-mm spot). In this simulation,[57] the payload consists of a copper-aluminum target. The rapid increase in pressure launches a shock wave that travels toward the left in quasi one-dimensional conditions.

One final FAIR beam-driven capability is high-energy proton microscopy using the proton microscope called PRIOR. High-energy proton microscopy can penetrate high-areal-density targets for diagnosing experiments on the fundamental properties of materials in extreme dynamic environments as generated by a spectrum of drivers including pulsed power generators, high-energy lasers, gas guns, or possibly small explosive-driven generators. PRIOR will use the high-energy (2 to 5 GeV), high-intensity (up to 2.5×10^{13} protons per pulse) proton beams from the SIS-100 synchrotron at FAIR. PRIOR will provide temporal and spatially resolved target mass density distributions with a spatial resolution of order 10 μm as well as temporal resolution below 10 ns. Early tests[72] at GSI have already shown an outstanding spatial resolution of 30 μm and current studies on PRIOR focus on achieving long-term reliability using radiation-resistant magnetic optics.

II. FOCUS AREAS FOR HED RESEARCH AT FAIR

Four principal focus areas for HED physics research have been identified by international workshops[73,74] that fully exploit FAIR's unique facility capabilities. Full realization of this research breadth will ultimately require the completion of FAIR's full capabilities as defined by the modular start version (MSV) plan.[75]

A. Properties of materials driven to extreme conditions of pressure and temperature relevant to planetary science

Exploration of the Solar System by robotic spacecraft and the discovery of extra-solar planets and brown dwarfs by orbital observation platforms represent some of the most exciting astronomical developments of the past three decades. The majority of extra-solar planets are now believed to be gas giants, like Jupiter. In addition, super-Earth-like planets have been hypothesized. It is believed that the core of these super-Earth planets, like the Earth, is mostly composed of iron. Assuming an Earth-like internal structure, models have been developed to assess the physical conditions that may exist at the interior of the super-Earths of different masses. These models predict that for planet mass between 1 and 10 times Earth mass, the pressures are in the range of 3.5 to 15 Mbar with temperatures in the range of 6000 to 10 000 K.[66,76,77] It is thus important, for example, to understand the thermophysical and transport properties of iron under these extreme conditions in order to further our understanding of planetary structure.

Observational data have raised many issues with existing models of planetary formation and structure. Predicting the internal structure of planets depends principally on the properties of compositional matter at extreme pressures or HED conditions. As previously discussed, FAIR heavy ion beams using the LAPLAS platform will be able to access a wide range of core planetary conditions to determine properties such as equation of state, optical properties, electrical conductivity, and thermal conductivity with a view to help discriminate between different planetary formation models.

B. Dynamic compression science

An existing challenge in dynamic compression and shock science is the characterization of phase transformations [in pressure–volume–temperature (P–V–T) phase space] with respect to melting, evaporation, freezing, solid-solid transformations, plasma phase transitions, critical points, etc., and their associated kinetic rates. Of interest is the observation that static and dynamic measurements do not always yield the same phase space behavior. Possible explanations include path-dependence in pressure, volume, and temperature space or the effect of strain rate (which can include both loading and release paths) on the transformation dynamics.[78] Key capabilities to resolve these unknowns include the ability to accurately and reproducibly create the desired high-entropy state and subsequently characterize these states dynamically.

The HIHEX scheme at FAIR is one technique being developed to access phase space regions around the critical points of various materials. Phase diagrams in the region of the critical point for many materials are not well determined,[1] because reproducing such conditions in the laboratory is challenging using standard dynamic compression techniques like shocks. One limitation has been that the values of pressure and temperature at the critical point are of order kilobar and eV, respectively, and producing these conditions in quasi-steady-state is difficult. Here, simulations show that ion-beam intensities around 10^{10} uranium ions are sufficient to access the critical point of many materials.[54,79,80]

Other important problems, of both fundamental and applied interest, are determining the thermophysical and transport properties of matter, including EOS, electrical conductivity, viscosity, and optical properties.[1,81–83] This information is critical to informing and validating theoretical models of material behavior during dynamic compression and for planetary physics.[84,85]

C. Strongly coupled plasma physics

Research on dense plasmas at FAIR will address the fundamental aspects of correlated many-body quantum systems. One prominent example is the still unresolved issue of hydrogen metallization. The possibility of a metallic hydrogen state was first theoretically predicted by Wigner and Huntington in 1935.[86] Metallic hydrogen is predicted to exist in the liquid state in the hot and gravitationally compressed interiors of large planets such as Jupiter and Saturn.[87] Understanding hydrogen EOS is critical to understanding and predicting the planetary structure.

There exists a rich history of theoretical and experimental work to create and study metallic hydrogen in the laboratory. Landau and Zeldovich discussed the possibility of a first-order insulator–metal phase transition in hydrogen and its connection to the liquid-gas phase transition.[88] Subsequent theoretical models of non-ideal plasmas predict the existence of such a transition at megabar pressures.[89] Research reported by Fortov *et al.* on quasi-isentropic compression of Deuterium showed a 20% increase in density at megabar pressures (1.4 Mbar) and the appearance of metal-like conductivity ($\sim 2 \times 10^4$ S/cm) when the density exceeded 1.4 g/cm^3. These results have been interpreted as a phase transition of the first order.[90] Other measurements of high hydrogen conductivity ($\sim 10^4$ S/cm), using shock reverberation techniques, have also been reported.[91–95]

Recent measurements of reflectivity in dynamically compressed deuterium at the Sandia Z Machine[9] and the National Ignition Facility[8] suggest a dielectric-metal transition at pressures of $\sim$2 Mbar and temperatures in the range of 1000 to 2000 K. These results differ from data obtained from laser-heated diamond-anvil cells[96] that indicate a much larger dependence of the transition pressure with the temperature.

The dielectric-metallic transition in solid hydrogen also shows a much lower temperature dependence in the 5 to 200 K range[97,98] for pressures around 4.5 to 5 Mbar. These measurements illustrate that the EOS and phase diagram of hydrogen, with specific regard to dielectric-metal transition, remains a grand-challenge of high-pressure physics. Thus, accurate experimental data in the warm-dense matter regime, a principal focus of HED@FAIR research, are critical to validate assumptions in theoretical models of these phenomena. Here, the time scales, uniformity, and volumes characterizing the experiments at FAIR will enable accurate measurement under complementary conditions, to help better understand these phenomena.

Another FAIR research area is the study of molecular fluids (such as H_2 and N_2) at Mbar pressures, where they are predicted to undergo phase transitions to various exotic (high-conductivity, metallic, polymeric) phases.[99] One specific focus area is elucidating the high-pressure thermodynamic properties of silicone dioxide (SiO_2) with a view to understanding conditions in the deep Earth interior. Multiple shock compression techniques are proposed to form and study high pressure states of matter including the fluid-fluid phase transition in silicate melts and phase transformation in silicate glasses or in crystalline silica. Time dependent density, including density jumps across shock fronts or during phase transition, and shock velocity will be measured by the PRIOR proton microscope.[100–102] Furthermore, the study of non-congruent phase transitions in composites is another topic of fundamental thermo-physical interest for investigation.[103]

Ionization potential depression (IPD) in strongly coupled plasmas has attained significant attention after experiments at LCLS with isochorically heated aluminum samples showed significant discrepancies with the widely used IPD model.[104] Experiments at the National Ignition Facility[105] and at the Orion laser,[106] measuring the ionization balance at ultra-high densities by x-ray scattering and x-ray spectroscopy, respectively, showed a significantly higher ionization than that predicted by standard theories of IPD. This motivates the need for an improved understanding and treatment of atomic physics in such strongly coupled systems.[107] Such strongly coupled degenerate plasmas, although at lower density, can be produced with very high quality, that is with a high level of homogeneity and at equilibrium conditions, by heavy-ion heating of tamped foils.

A number of research topics in dynamic compression science and strongly coupled plasma physics can already be started using existing GSI facilities. For example, developing necessary experimental and measurement techniques, like the use of high-resolution x-ray transmission spectroscopy,[51] are a present focus of plasma physics research at GSI. Another current research topic includes the EOS investigation of non-ideal noble gas, shock-driven plasmas with coupling parameter $\Gamma \sim 1$.[108] Here, density measured using the PRIOR proton microscope, along with temperature and conductivity diagnosis, will advance our present knowledge of the EOS of matter in this strongly coupled plasma regime.

D. Nuclear photonics

Nuclear Photonics encompasses a rapidly evolving field of research that explores the interaction between strong electromagnetic fields driven by ultra-high-intensity lasers and nuclei. It is enabled by high-power, short-pulse laser facilities together with targets designed for the production of intense particle or photon beams. For example, the present PHELIX laser at GSI holds a world record for short pulse laser generated neutrons with a reproducible neutron output of 10^{11} neutrons per shot and with a forward directed angular fluence of 1.4×10^{10} neutrons per steradian.[109] PHELIX has also demonstrated MeV electron and gamma ray production.[110] The application of these intense beams promises significant advantages for the diagnosis of FAIR-generated matter at extreme conditions. For example, laser-generated protons, neutrons, and x-rays can be directly employed for radiographic imaging. An intense laser-generated and moderated neutron beam[111] also shows promise for measuring the temporally resolved temperature of shocked or isochorically heated matter using neutron resonance spectroscopy.[112] Another example is the excitation of the exotic nuclei available at a heavy ion accelerator in laser-generated plasma.[113] Nuclear Photonics is an important area for collaboration with other facilities researching extreme matter worldwide.

III. FAIR EXPERIMENTAL INFRASTRUCTURE FOR HED-PHYSICS RESEARCH

A. The evolving FAIR HED experimental capability

In 2018, GSI completed the upgrade of the SIS-18 accelerator ring.[114] This activity was necessary for injecting ions into the SIS-100. Starting in 2019, the SIS-18 is being gradually driven to higher and higher intensities. During this start-up phase, FAIR and GSI will support a limited research program to test the improved capabilities of the SIS-18 and to test the necessary equipment and proposed experimental techniques that have been developed by the FAIR collaborations. This operation period is called FAIR Phase 0. HED-physics Phase-0 experiments are using GSI's existing facilities: the high-energy high-intensity laser PHELIX, the Z6 target station of the UNILAC, and the high-energy cave (HHT) at the SIS-18. From 2019 until the start of commissioning of the SIS-100 synchrotron, there will be approximately three months of beam time per year for the FAIR Phase-0 program.

The Phase-0 program is open to international users by means of a proposal process. Phase 0 operations will also be used to test and enhance key diagnostic systems for eventual use on FAIR. Planned activities include commissioning the second PRIOR microscope (PRIOR II) based on electromagnet focusing elements. Expected improvements to the PHELIX laser include improving laser focus quality, improving repetition rate operation. These will complement recent upgrades to the facility like the commissioning of a VISAR system at the Z6 experimental area for laser-driven shock experiments, and the construction of a laser beam line to the HHT experimental area.

Starting from 2025 on, FAIR will utilize the pump-probe technique where heavy-ion drivers pump the material to HED states and a variety of diagnostics are then used to study the HED-matter properties. The unique pump capability of FAIR is driven by the SIS-100 synchrotron that will accelerate intense beams of protons and heavy ions to a magnetic rigidity of 100 T m. (Fig. 2). For the first experiments during the start period, the SIS-100 will provide a 75 to 100 ns, 0.4–2.0 GeV/u uranium beam with 1×10^{11} ions per pulse. Simulations of these conditions show that the HIHEX scheme can create relatively large volumes of energetic matter with a range of heating options from isochoric to isentropic. Measurement of transport properties, like thermal conductivity, electrical conductivity, and viscosity under extreme conditions, will be possible. Full SIS-100 performance will realize 10 GeV/u uranium ions with 5×10^{11} ions per pulse, although the experimental utilization of the SIS 100 for HED-physics purpose will likely not require more than 2.7 GeV/u.

HED physics experiments will utilize a dedicated beam line in a fully shielded experimental cave (Fig. 6), the so-called APPA cave, where heavy ion beams, proton beams, and laser beams will be available. Installation of the first experimental infrastructure will commence in 2021. Commissioning without a beam is expected in late summer 2024. HED-physics research is about pump-probe experiments, and thus the GSI SIS-18 and the FAIR SIS-100 synchrotrons, in combination with bunch compression capabilities to produce intense, short (<100 ns) beam pulses, are ideal plasma physics drivers. In addition, high-energy lasers like PHELIX[115] at GSI or the envisaged Helmholtz laser beam line[116] at FAIR provide essential diagnostic tools for HED-physics research.

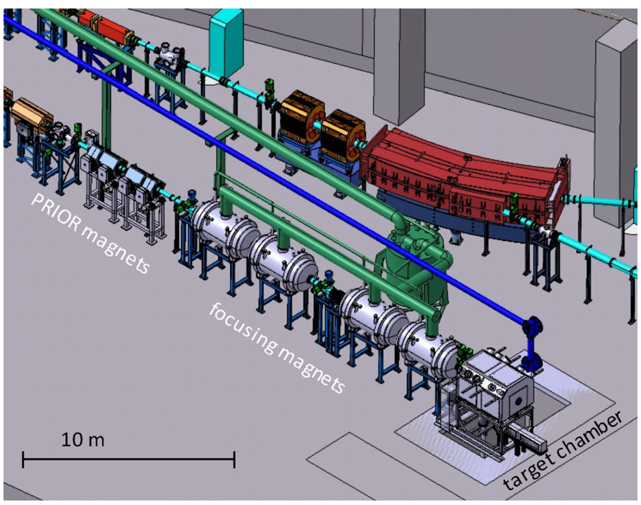


FIG. 6. The HED@FAIR beam line is located in the APPA Cave at FAIR. This experimental area is dedicated to Plasma Physics, high-energy-density physics, atomic physics, and bio and materials research.

B. Planned and envisaged diagnostics

In order to diagnose the large samples of HED matter, a suite of diagnostics driven by a powerful driver is highly desirable. Active backlighting with highly penetrating laser-accelerated particles or x-ray radiation will be the primary diagnostic tools to probe plasma parameters and the structural information of HED matter. This plan is motivated by the results obtained in the last decade by facilities like NIF-ARC, OMEGA-EP, PETAL, and the Z-Beamlet, for example.[117] As such, the facility at FAIR will profit from the tremendous progress made by laser-based secondary radiation sources and their application to x-ray scattering, x-ray absorption spectroscopy (XANES), and x-ray radiography.[118] In general, FAIR will also benefit from the diagnostic expertise developed and employed at FEL facilities for HED-physics research world-wide.

Probing the millimeter-size high-Z targets, foreseen in the HED-physics research program, will require highly penetrating hard (>100 keV) x-ray sources, typically obtained from laser systems delivering focused intensities in excess of 10^{18} W/cm^2. Directed sources of soft x-ray radiation can be generated via the oscillation of laser-accelerated electrons (betatron radiation). Simulations[119] predict x-ray and gamma-ray energies well beyond the range necessary for the FAIR backlighter. Such sources are of particular interest as the divergence in the milli-radian range is ideally suited to probe the millimeter-sized samples that will be generated at FAIR. It enables, in particular, separating the radiation generation chamber from the ion-interaction chamber, which drastically simplifies the experimental setup. Other secondary radiation sources with large diagnostic potential for dense samples include laser-accelerated protons,[120] neutrons,[111] and electrons.[121] The first proposal for a double-beam line, high-power multi-kilojoule diagnostic laser has been made in the initial version of FAIR, and a space located between the APPA cave and the High-Energy Storage Ring has been reserved for this high-energy petawatt laser. Realization of this laser system, however, is not planned for the early start of FAIR due to budget constraints and will await future longer-term FAIR funding opportunities.

The proposed pump-probe laser system, to be operational for the first FAIR experiments, is a more modest system with a pulse energy of 100 J at a wavelength of 527 nm, pulse durations between 100 ps and 10 ns, and focused intensities in the range of 10^{12} to 10^{16} W/cm^2. This system is capable of driving intense laser-plasma sources for backlighting from XUV to x-rays with approximately 10 keV energy. These sources will enable a wide range of x-ray backlighting diagnostic schemes on lower-Z targets, such as keV radiography using pinhole imaging, VUV opacity measurements, x-ray near-edge absorption structure, x-ray diffraction, and x-ray scattering applications.[122]

Proton radiography or microscopy is a powerful technique for probing the interior of dense objects in dynamic experiments by mono-energetic beams of energetic protons using a system of magnetic lenses for imaging and correction of image aberrations.[123] With this technique, one can measure sub-percent variations in the areal density of samples with micrometer spatial resolution and nanosecond temporal resolution. Proton radiography with magnetic lenses was invented in the 1990s at the Los Alamos National Laboratory (LANL) as a diagnostic to study dynamic material properties under extreme pressures, densities, and strain rates.[124] Since that time, proton radiography and microscopy facilities have also been commissioned at the Institute for Theoretical and Experimental Physics (ITEP),[125,126] and at the Institute for High Energy Physics (IHEP)[127–129] in Russia. As previously mentioned, FAIR will be equipped with the PRIOR proton microscope.

C. The HED@FAIR collaboration

High energy density physics is part of the APPA (atomic plasma physics and applications) pillar at FAIR. APPA is an umbrella organization consisting of four collaborations: BIOMAT (Biology and Material Science), FLAIR (Facility for Low-Energy Antiproton and Heavy Ion Research), SPARC (Stored Particles Atomic Research Collaboration), and HED@FAIR (High energy density and plasma physics). APPA constitutes one of the four major scientific pillars for FAIR.[130]

The collaboration is open to scientists or institutions that are interested in participating in the definition, development, and realization of the HED program at FAIR. In addition, the collaboration is active in planning for the FAIR Phase-0 research program that breaches the gap between the present and the startup of FAIR Day one experiments in 2025. In FAIR Phase 0, the collaboration will use the existing GSI facilities (PHELIX, the Z6 target station at the UNILAC, and the high-energy cave HHT with the SIS-18) to prepare the HED-physics scientific program that will ultimately utilize the APPA cave.

IV. CONCLUSION

FAIR will provide the international research community with a platform for high energy density scientific research that exploits the unique attributes of FAIR as a WDM and HED-matter driver. These unique attributes derive from using the world's highest intensity relativistic beams of heavy nuclei, coupled with laser-driven probes, to create and investigate macroscopic quantities of highly energetic and dense-plasma states of matter in local thermal equilibrium. FAIR-based research will both complement and benefit from the synergies attendant with the international HED community and other facilities already exploring HED science, for example, collaborations on the joint development of diagnostic or experimental techniques that are of mutual benefit to any HED facility or experiment. As such, FAIR will be an essential capability within and contributor to the rapidly developing international field of HED-physics research.

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