# STUDIES OF HIGH ENERGY DENSITY MATTER USING INTENSE ION BEAMS AT FAIR AT DARMSTADT: THE HEDgeHOB COLLABORATION

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*Abstract*

Due to its relevance to numerous areas of basic and applied physics and because of its potential for many useful industrial applications, the subject of High Energy Density Physics (HEDP) has been a very active area of research over the past many decades. Different static as well as dynamic experimental schemes are employed for this purpose. Recent advancements in the technology of bunched intense particle beams have led scientists to propose a new, very efficient scheme to generate large samples of HED matter in the laboratory by isochoric and uniform heating of solid targets by these ion beams. The Helmholtzzentrum für Schwerionenforschung (GSI), Darmstadt is a well known laboratory worldwide due to its unique accelerator facilities. Construction of the new Facility for Antiprotons and Ion Research (FAIR) will increase the existing accelerator capabilities substantially. Research on HEDP will be one of the major research areas that will benefit from this facility. Extensive theoretical work has been carried out during the past years to propose novel HED physics experiments that can be done at FAIR. In this paper we present a brief summary of this work.

## INTRODUCTION

States of matter that correspond to an energy density of $10^{11}$ J/m$^3$ or equivalently, 1 Mbar pressure, and above, are classified as High Energy Density (HED) states. The importance of this subject is underscored by the fact that it spans over numerous, very interesting areas of basic and applied physics. For example, astrophysics, planetary sciences, geophysics, inertial fusion and many others. Moreover, it has great potential for many useful industrial applications. Due to significant progress in the high pressure technology over the past fifty years, substantial progress has been made in studying the physics of HED matter. Several static as well as dynamic schemes have been used for this purpose.

Substantial progress has been made during the past decade in the technology of strongly bunched, well focused, high quality intense particle beams, especially at the Helmholtzzentrum für Schwerionenforschung (GSI), Darmstadt. In fact, GSI is one of the leading accelerator laboratories worldwide which at present, has a heavy ion synchrotron, SIS18, that delivers intense particle beams of all stable species, from protons up to uranium. The new huge international accelerator project, FAIR (Facility for Antiprotons and Ion Research) at Darmstadt, which includes building of a new much more powerful synchrotron, SIS100, is now entering into construction phase. When working at its full capacity, this new synchrotron will deliver a uranium beam with an intensity, N = 5 $\times$ $10^{11}$ ions that will be delivered in a single bunch, 50 – 100 ns long. A wide range of particle energy (400 MeV/u – 2.7 GeV/u) will be available that will give great flexibility to the experiment designers. The transverse intensity distribution will be Gaussian and the beam could be focused down to a FWHM = 1 mm. These beam parameters lead to a specific energy deposition of about 150 KJ/g and a specific power deposition on the order of 5 TW/g in solid lead. These unprecedented beam parameters will allow one to carry out novel experiments in this very important field of physics.

To facilitate the design and construction of the experimental facilities at FAIR and later to organize the experiments at these facilities, an international collaboration named HEDgeHOB (High Energy Density Matter Generated by Heavy Ion Beams) has been formed. The theoretical work presented in this paper has served as the basis for the HEDgeHOB scientific proposal.

## HEDgeHOB SCIENTIFIC PROPOSAL

In this section we present a brief description of the schemes of the different experiments that will be carried out at FAIR by the HEDgeHOB collaboration.

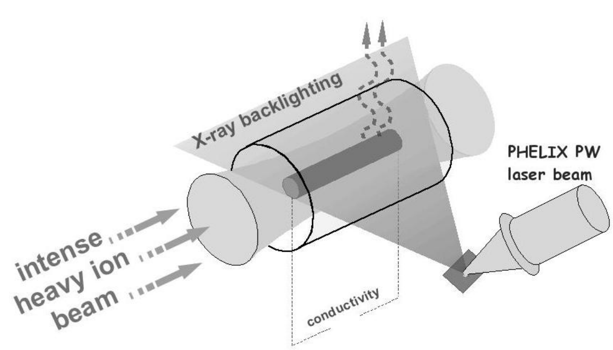


Figure 1: HIHEX scheme using a solid cylindrical target.

### *HIHEX: Heavy Ion Heating and Expansion*

This scheme generates HED matter by isochoric and uniform heating of a solid or a porous target by the ion beam that is followed by isentropic expansion of the heated material. Figure 1 shows proposed beam–target configuration for a typical HIHEX experiment in which the target is a solid cylinder that is enclosed in a cylindrical shell of a strong material like LiF or sapphire which is transparent to infrared, visible and ultraviolet radiation. A gap with suitable dimensions exists between the sample and the outer shell. The ion beam is focused on one face of the cylindrical sample and the target length is assumed to be shorter than the ion range so that the Bragg peak does not lie inside the target. This leads to a uniform energy deposition in the longitudinal direction. Since the particle intensity distribution is Gaussian in transverse direction, uniformity of energy deposition in the radial direction is ensured by considering the target radius to be much less than the full width at half maximum (FWHM) of the Gaussian distribution. The length of the ion pulse is assumed to be less than the material hydrodynamic timescale that leads to an isochoric energy deposition.

The heated material expands in the cavity and thermalizes as a result of multiple reflections between the surrounding wall and the axis that leads to fairly uniform physical conditions in the sample. The transparent wall would facilitate the diagnostics of the sample. By varying the beam intensity, the final temperature can be controlled whereas by changing the gap between the sample and the surrounding wall, the required final density can be achieved. For further details including sophisticated two-dimensional hydrodynamic simulations, see [1]. These simulations have shown that all the important HED states of materials of interest can be accessed using the high intensity ion beam that will be available at the FAIR.

### *LAPLAS: Laboratory Planetary Sciences*

This experimental scheme proposes low–entropy compression of a material like frozen hydrogen or ice that is enclosed in cylindrical shell of a high-Z material like gold or lead. Two configurations can be used in these experiments as discussed below.

#### Case I: LAPLAS Using a Hollow Beam

The proposed beam–target geometry is shown in Fig. 2. The target consists of a cylinder of frozen sample material (hydrogen or water) that is surrounded by a thick shell of a heavy material, typically gold or lead. One face of the target is irradiated with an intense heavy ion beam that has an annular (ring-shaped) focal spot. We assume that the inner radius of the annulus is larger than the radius of the sample material which is a necessary condition to avoid direct heating of the sample by the ion beam. Moreover, we consider that the outer radius of the focal spot ring is smaller than the outer radius of the surrounding shell. A layer of cold material from the outer shell known as ”pusher” or ”payload”, is created between the sample material and the beam–heated region. The payload plays an important role in placing the compression on the desired adiabat. It is also seen that a cold shell around the beam-heated zone remains as a tamper that confines the implosion for a longer time. For further details see [2–4].

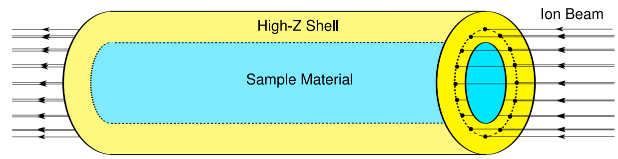


Figure 2: LAPLAS scheme using a beam with an annular focal spot.

The target length is assumed to be less than the range of the driver ions so that the energy deposition in the longitudinal direction is uniform. The pressure in the beam heated region increases substantially that launches a shock wave inwards, along the radial direction. The shock wave enters the pusher and is subsequently transmitted into the hydrogen and is reflected at the cylinder axis. The reflected shock wave moves outwards along the radial direction and is re–reflected at the hydrogen–gold boundary. The boundary continues to move inwards, thereby compressing the hydrogen slowly. This scheme generates a low–entropy compression that leads to a very high material density with a relatively low temperature. Simulations have shown that using the parameters of the SIS100 beam at the FAIR, one would achieve a hydrogen density of 1 – 2 g/cm$^3$, a pressure of 3 – 15 Mbar and a temperature of a few thousand K. This scheme is therefore more suited to study the problem of hydrogen metallization [2–8].

#### Case II: LAPLAS Using a Circular Beam

This scheme is shown in Fig. 3. In this case the hydrogen is also directly heated by the beam, but since the pressure in the surrounding shell is orders of magnitude higher than in hydrogen, the hydrogen is still compressed to very high densities. However, the final temperature of hydrogen in this case is much higher (of the order of a few eV) than that in the previous one. This scheme is suited for studying the planetary interiors. Numerical simulations have shown that using the FAIR high intensity beam, one can compress hydrogen to a density of 1.2 g/cm$^3$ while a pressure of the order of 10 Mbar can be achieved [9].

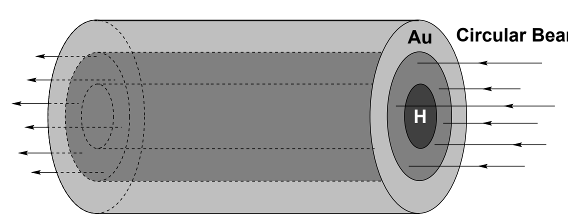


Figure 3: LAPLAS scheme using a beam with a circular focal spot.

We also carried out simulations using water as sample material. In this study we consider an intensity of $10^{11}$ 1 GeV/u uranium ions that are delivered in a single bunch, 50 ns long. The target length is 5 mm which is shorter than the range of the projectile particles so that the energy deposition is uniform in the longitudinal direction. The radius of the sample is 200 $\mu$m. In these simulations we use a semi-empirical equation of state model [10] for Au and data based on Quantum Molecular Dynamic (QMD) simulations for water published in [11].

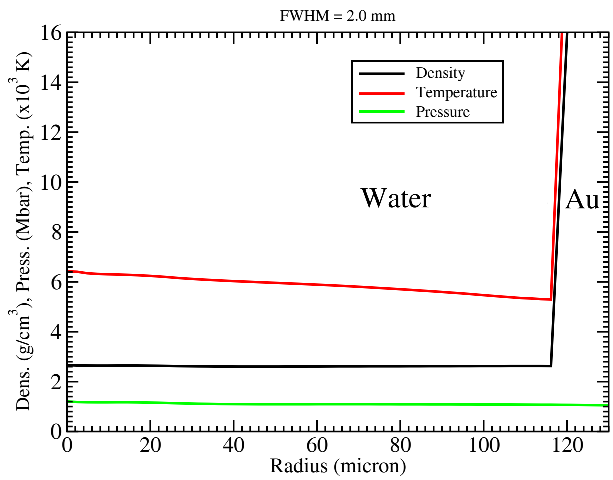


Figure 4: $\rho$, T and P vs radius in the water layer at the time of maximum compression for a beam FWHM = 2 mm.

In Fig. 4 we plot the density, temperature and pressure along the radius (in the water layer) using a beam FWHM = 2 mm at the time of maximum compression. It is seen that a density of 2.6 g/cm$^3$, a pressure of 1.2 Mbar and a temperature of about 5000 K is achieved. These parameters correspond to the plasma state of water. It has been found that using different values of the beam parameters (smaller FWHM and higher intensities), one may access higher densities corresponding to the superionic state in which the protons become mobile in the oxygen [11].

### *Ramp Compression*

Figure 5 shows a schematic diagram of this proposed experiment which consists of a cylindrical disc of high-Z reservoir followed by the sample material and the two are enclosed in a strong cylindrical casing. The ion beam is incident on the reservoir and the ions are completely stopped in the material. The high pressure due to the Bragg peak launches a shock in the longitudinal direction that releases material when it arrives at the reservoir boundary. The expanding material piles up against the sample and pressure builds up slowly that drives a shockless compression of the sample material. Simulation show a 60 % compression of an Al sample while the temperature and pressure are of the order of 800 K and 1 Mbar respectively. This scheme is therefore suitable to study material properties under dynamic conditions.

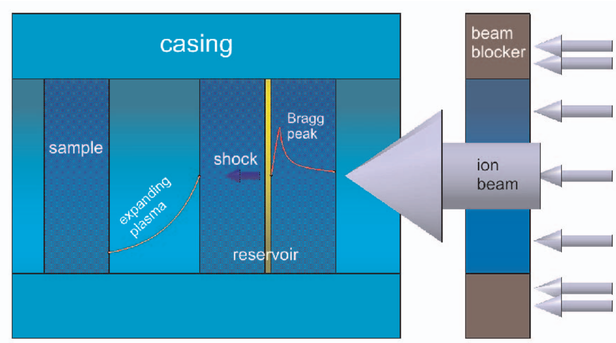


Figure 5: Proposed beam–target geometry for a ramp compression scheme.

## CONCLUSIONS

Theoretical work presented in this paper has shown that using the intense heavy ion beams that will be available at the Facility for Antiprotons and Ion Research, will allow the scientists to study HEDP in those regimes which have previously not been accessible by the traditional methods of research.

## ACKNOWLEDGEMENTS

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