

# High Energy Density Matter Research Using Intense Heavy Ion Beams at the Future FAIR Facility at Darmstadt: The HEDgeHOB Collaboration

N A Tahir<sup>1</sup>, I V Lomonosov<sup>2</sup>, A Shutov<sup>2</sup>, V Kim<sup>2</sup>, V E Fortov<sup>2</sup>, A R Piriz<sup>3</sup>, G Wouchuk<sup>3</sup>, M C Serna Moreno<sup>3</sup>, J J Lopez Cela<sup>3</sup>, D H H Hoffmann<sup>1,4</sup> and C Deutsch<sup>5</sup>

<sup>1</sup>Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany

<sup>2</sup>Institute for Problems in Chemical Physics, Chernogolovka, Russia

<sup>3</sup>E.T.S.I. Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain

<sup>4</sup>Institut für Kernphysik, TU Darmstadt, 64289 Darmstadt, Germany

<sup>5</sup>LPGP, Université Paris-Sud, 91405 Orsay, France

E-mail: n.tahir@gsi.de

**Abstract.** This paper reports an overview of the extensive theoretical work that has been carried out over the past few years to explore the capabilities of intense beams of energetic heavy ions to study High Energy Density (HED) states in matter. This work has shown that an intense ion beam can be a very efficient driver for disparate experimental schemes suitable to study this important field of research. These include **HIHEX** [**H**Heavy **I**on **H**eating and **E**Xpansion] that involves generation of required HED states by isochoric and uniform heating of matter by the ion beam that is followed by isentropic expansion. Another proposed experimental set up is named **LAPLAS** that stands for **L**aboratory **P**lanetary **S**ciences. This latter experiment has been designed to generate physical conditions that are expected to exist in the interiors of the giant planets. This is achieved by a low-entropy compression of the sample material (hydrogen or ice). A third scheme involves a ramp (shockless) compression of a test material which will allow one to investigate the material properties, like yield strength, under dynamic conditions.

## 1. Introduction

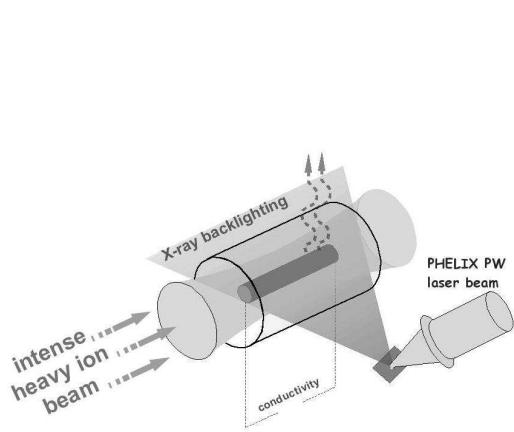
Significant progress in the development of strongly bunched, well focused, high intensity particle beams [1] have lead to the idea of using these beams to induce High Energy Density (HED) states in matter by isochoric and uniform heating of solid targets [2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13]. In such a scheme, one generates exotic states of high entropy and high pressure as a result of direct energy deposition by the projectile particles over extended volumes of solid matter, which is in contrast to the traditional methods that employ shock compression of matter [14, 15, 16, 17, 18, 19]. It has also been proposed to use intense collimated ultra-short ion beams generated by petawatt lasers for this purpose [20]. However, ion beams generated by traditional accelerators have numerous advantages over the laser generated beams [21].

The above problem is of considerable interest to the Gesellschaft für Schwerionenforschung (GSI), Darmstadt as it is the leading laboratory worldwide which has accelerator facilities that deliver intense heavy ion beams including uranium. The existing heavy ion synchrotron, SIS18,

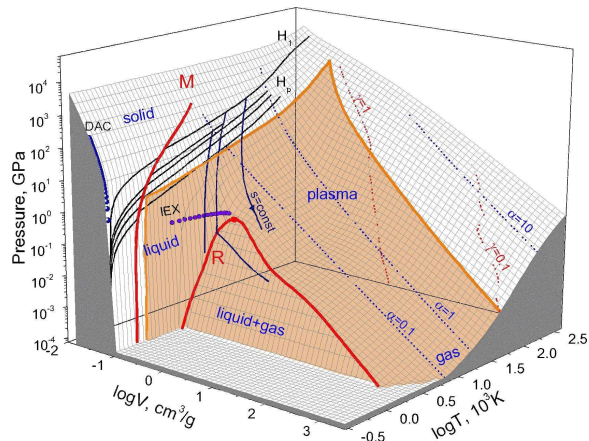
can generate a uranium beam with an intensity of  $4 \times 10^9$  ions of  $U^{+73}$  delivered in a single bunch, 130 ns long while the particle energy is of the order of 400 MeV/u. Construction of the future facility **FAIR** [**F**acility for **A**ntiprotons and **I**on **R**esearch] will substantially increase the accelerator capabilities of the GSI. The new synchrotron, SIS100, will generate a uranium beam with an intensity of  $5 \times 10^{11}$  ions per bunch and a wide range of particle energies, 400 MeV/u - 2.7 GeV/u will be available. The bunch length will be reduced to about 70 ns and the beam can be focused to a spot size of 1 mm radius. Extensive theoretical work that has been carried out during the past few years, has shown that a number of different experimental schemes can be employed to study HED physics using the SIS100 beams as summarized below.

Using the existing accelerator facilities, interesting experiments on heating matter using intense ion beams have been carried out and reported elsewhere [22]. Moreover necessary diagnostics for these experiments are also being developed [23]

## 2. HIHEX Experimental Scheme



**Figure 1.** Schematic diagram of cylindrical HIHEX using solid material.



**Figure 2.** Equation-of-state surface for lead in P–V–T variables (logarithmic scale). The colored region bounded by corresponding isochor and isentrope shows the parameter region accessible with SIS100 heavy ion beams.

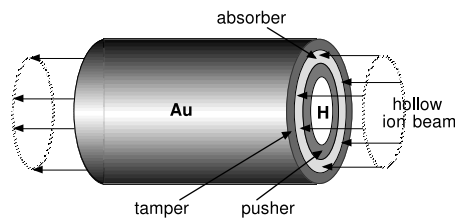
Figure 1 shows a proposed configuration for the HIHEX experiment [13, 6]. A solid cylindrical target is enclosed in a cylindrical shell made of a strong material like LiF or sapphire which is transparent to infrared, visible and ultraviolet radiation and there is a gap between the two materials. The beam is incident on one face of the cylinder and the particle range is much larger than the cylinder length. The Bragg peak therefore does not lie inside the target that ensures uniform energy deposition in longitudinal direction. Uniform energy deposition in radial direction is achieved by assuming the beam radius to be much larger than the cylinder radius. The heated material expands in the cavity and due to multiple reflections between the cavity walls and the cylinder axis, the material thermalizes in a few microsec. The transparent wall allows for temperature measurements using an optical pyrometer [23]. The sample pressure will be measured using laser interferometric techniques while the density distribution will be determined using proton and ion radiography. Protons will be generated by the petawatt FELIX beam whereas the ions will be provided by an additional diagnostic beam provided by SIS18. Typical calculations are reported in [6, 8]. Figure 2 shows a phase diagram of lead on a P-T-V

surface. It is seen that using the HIHEX technique, one may study all those regions of the phase diagram that are not accessible using the traditional methods. These experiments will therefore provide a wealth of very useful new scientific information on the thermophysical properties of HED matter.

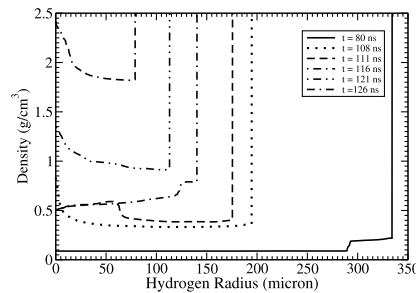
### 3. LAPLAS Experimental Scheme

Two different experimental setups have been proposed for the LAPLAS experiment as shown in Figs. 3 and 4 respectively. In the former case, a hollow beam with an annular focal spot is used to drive the target that avoids direct heating of the sample material (frozen hydrogen). The shock generated by the high pressure in the surrounding gold shell reverberates between the axis and the hydrogen-gold boundary (as shown in Fig. 4) that leads to a low-entropy compression. Numerical simulations have shown that one can achieve a density of  $1 - 3 \text{ g/cm}^3$ , a pressure of  $5 - 20 \text{ MBar}$  and a temperature of a few thousand K in the compressed hydrogen [8, 24, 10]. These are the theoretically predicted physical conditions for hydrogen metallization.

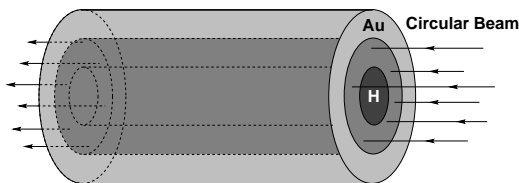
The latter scheme uses a circular beam spot that heats the sample material as well, but the pressure in the surrounding hot gold shell is still orders of magnitude higher than that in hydrogen. One therefore achieves a high degree of compression (density of  $1.2 \text{ g/cm}^3$ ) in hydrogen, a pressure of about  $11 \text{ MBar}$  but a temperature of few eV (see Fig. 6). These are the physical conditions expected to exist in the interiors of the giant planets.



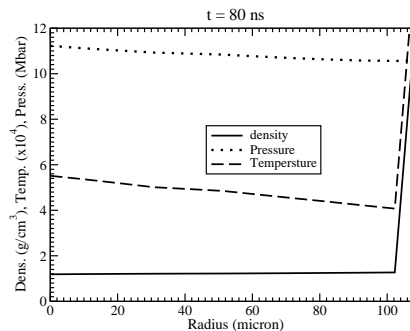
**Figure 3.** LAPLAS implosion scheme using an annular beam spot.



**Figure 4.** Density vs radius in hydrogen at different times.



**Figure 5.** LAPLAS implosion scheme using a circular beam spot.



**Figure 6.** LAPLAS implosion scheme using a circular beam spot.

#### 4. Ramp Compression Experimental Scheme

Figure 7 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 suitable to study material properties under dynamic conditions.

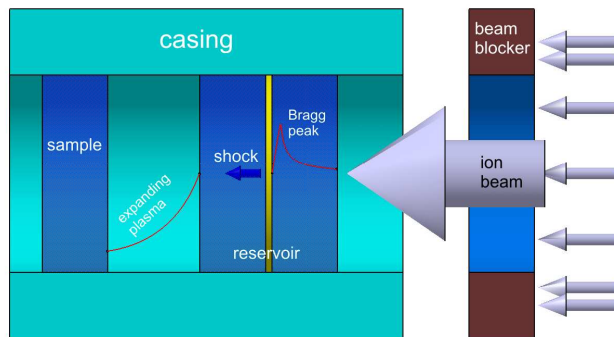


Figure 7. Ramp compression configuration.

#### References

- [1] Henning W F 2004 *Nucl. Instrum. Methods Phys. Res. B* **214** 155.
- [2] Tahir N A et al. 1999 *Phys. Rev. E* **60** 4715.
- [3] Tahir N A et al. 2000 *Phys. Rev. E* **61** 1975.
- [4] Tahir N A et al. 2001 *Phys. Rev. E* **63** 036407.
- [5] Tahir N A et al. 2004 *Laser Part. Beams* **22** 485.
- [6] Tahir N A et al. 2005 *Phys. Rev. Lett.* **95** 035001.
- [7] Tahir N A et al. 2005 *Phys. Rev. Lett.* **94** 135004.
- [8] Tahir N A et al. 2005 *Nucl. Instrum. Methods Phys. Res. A* **544** 16.
- [9] Tahir N A et al. 2007 *Laser Part. beams* **25** 295.
- [10] Piriz A R et al. 2002 *Phys. Rev. E* **66** 056403.
- [11] Piriz A R et al. 2005 *Phys. Rev. E* **72** 056313.
- [12] Piriz A R et al. 2005 *Nucl. Instrum. Methods Phys. Res. A* **544** 27.
- [13] Hoffmann D H H et al. 2005 *Laser Part. Beams* **23** 47.
- [14] Vladimirov A S 1984 *JETP Lett.* **39** 85.
- [15] Gregori G et al. 2006 *Phys. Rev. E* **74** 026402.
- [16] Nellis W J et al. 1992 *Phys. Rev. Lett.* **68** 1992.
- [17] Weir S T et al. 1996 *Phys. Rev. Lett.* **76** 1860.
- [18] Cauble R et al. 1993 *Phys. Rev. Lett.* **70** 2102.
- [19] Koenig M et al. 1995 *Phys. Rev. Lett.* **74** 2260.
- [20] Snavely R A et al. 2003 *Phys. Rev. Lett.* **91** 125004.
- [21] Tahir N A et al. 2006 *J. Phys. IV France* **133** 1059.
- [22] Udrea S et al. 2007 *Nucl. Instr. Met A* **577** 257.
- [23] Ni P et al. 2006 *J. Phys. IV France* **133** 977.
- [24] Tahir N A et al. 2001 *Phys. Rev. E* **63** 016402.