

# APPLICATION OF PARTICLE ACCELERATORS TO HIGH ENERGY DENSITY PHYSICS RESEARCH: THE HEDgeHOB COLLABORATION

N. A. Tahir, Th. Stöhlker, GSI Darmstadt, 64291 Darmstadt, Germany  
 A. Shutov, I.V. Lomonosov, V.E. Fortov, IPCP, Chernogolovka, Russia  
 R. Redmer, University of Rostock, 18051 Rostock, Germany  
 A. R. Piriz, University of Castilla-La Mancha, 13071 Ciudad Real, Spain

## Abstract

In this paper we describe an ion beam driven experimental scheme which is suitable to study planetary physics in the laboratory. Detailed numerical simulations have shown that an intense ion beam can implode a sample material like hydrogen and water to extreme conditions of density, temperature and pressure that are expected to exist in the interiors of the giant planets in our solar system. The importance of this subject is underscored by the discovery of over 400 extrasolar planets. This experiment which is named LAPLAS (Laboratory PLANetary Science), will be performed at the Facility for Antiprotons and Ion Research (FAIR) at Darmstadt.

## INTRODUCTION

High Energy Density Physics (HEDP) is one of the most active areas of research which spans over numerous disciplines of physics. For example, astrophysics, planetary physics, geophysics, inertial fusion and many others. Theoretical investigations have shown that intense particle beams are an efficient new tool to study HEDP [1, 2]. The heavy ion synchrotron, SIS100, to be built at Facility for Antiprotons and Ion Research (FAIR) at Darmstadt, will be one of the most powerful accelerators in the world. According to the design parameters, it will generate a uranium beam with an intensity,  $N = 5 \times 10^{11}$  ions that will be delivered in a single bunch, 50–100 ns long. An extensive program named HEDgeHOB [3] has been proposed to carry out HEDP research at FAIR. Four different types of experiments have been designed for this purpose. One of these experiments named LAPLAS that stands for Laboratory Planetary Sciences, has been proposed to study interiors of the giant planets in our solar system as well as those of the exoplanets. In the present paper we present numerical simulation results that demonstrate the feasibility of such a scheme.

## LABORATORY PLANETARY SCIENCE STUDIES

The beam–target geometry of the LAPLAS experimental scheme is shown in Fig. 1. The target consists of a cylinder of frozen sample material (for example, hydrogen or water which are expected to be abundant in giant planets) that is surrounded by a thick shell of a heavy material. 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.

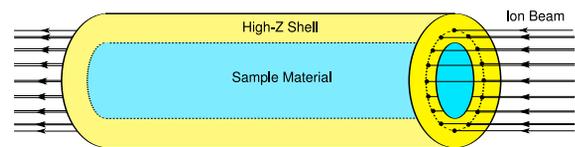


Figure 1: Beam–target configuration for LAPLAS experiment

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, is subsequently transmitted into the sample and then reflected at the cylinder axis. The reflected shock wave moves outwards along the radial direction and is again re-reflected at the sample–shell boundary. The boundary continues to move inwards, thereby compressing the sample slowly. This scheme generates a low–entropy compression of the sample material that leads to ultra–high densities, ultra–high pressures, but relatively low temperatures. These physical conditions are expected to exist in the interiors of the giant planets.

## SIMULATION RESULTS

In this study we consider a target that is made of solid water surrounded by a tungsten shell. The target length is  $L = 7$  mm, the radius of the sample (water) layer,  $R_i = 0.2$  mm and the outer target radius,  $R_o = 3$  mm. The ion energy is considered to be 1.5 GeV/u and the bunch length is 50 ns. The inner radius of the annular ring is,  $R_1 = 0.4$  mm and the outer radius is,  $R_2 = 1.4$  mm. We have considered different values of the beam intensity,  $N$ , including,  $10^{11}$ ,  $3 \times 10^{11}$  and  $5 \times 10^{11}$  ions per bunch, respectively.

We have carried out numerical simulations of the implosion of the above target using a 2D hydrodynamic code, BIG2 [4]. For tungsten we use a semi–empirical equation-of-state (EOS) [5] while for water, we use the EOS described in reference [6]. The ion energy loss in the target

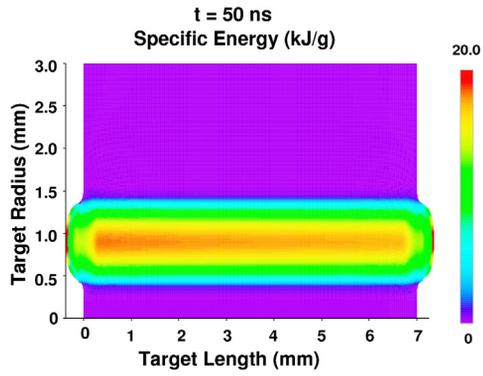


Figure 2: Specific energy distribution at t = 50 ns.

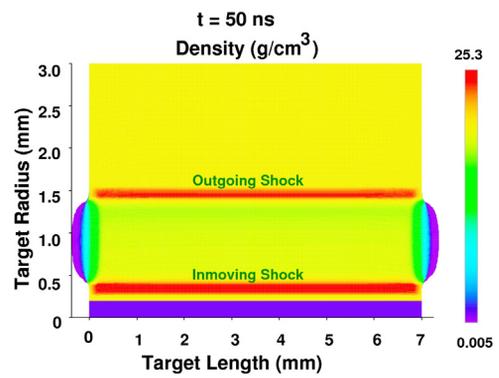


Figure 5: Density distribution at t = 50 ns.

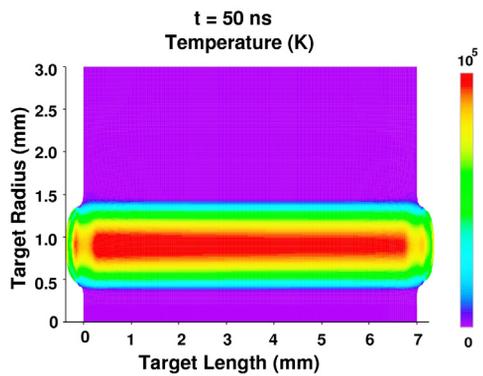


Figure 3: Temperature distribution at t = 50 ns.

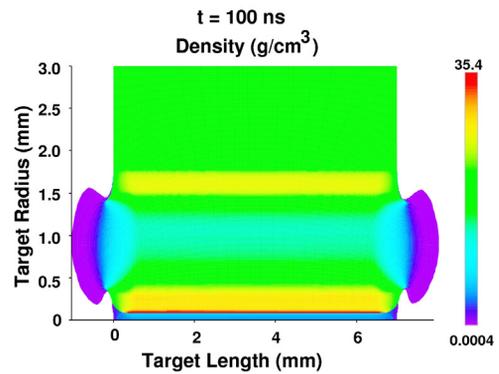


Figure 6: Density distribution at t = 50 ns.

is calculated using the SRIM code [7], which is based on cold stopping model. This is a reasonable approximation because the target temperature is not very high and the ionization effects on the stopping can be neglected.

In Fig. 2 we present the specific energy deposition in the target in r-Z plane at t = 50 ns, a time when the beam has just delivered its total energy. The beam is incident

at the right side of the target and the particles penetrate through the cylinder, thereby depositing energy uniformly along their trajectories. It is seen that the specific energy deposition at the maxima of the Gaussian distribution in the W shell is about 20 kJ/g. The corresponding temperature distribution is presented in Fig. 3 that shows a maximum temperature of the order of  $10^5$  K. The pressure distribution generated in the target is presented in Fig. 4 which shows a maximum pressure of 3.7 Mbar. The high pressure in the W

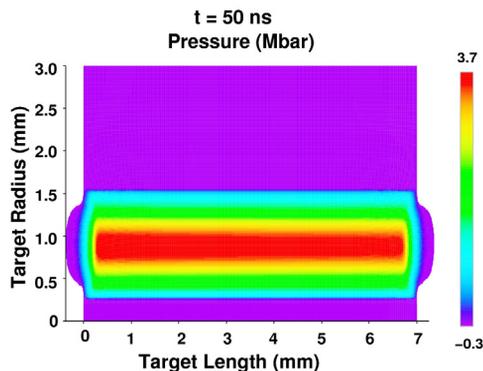


Figure 4: Pressure distribution at t = 50 ns.

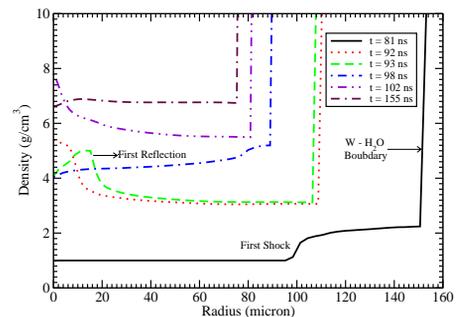


Figure 7: Density vs radius in the water region at different times.

shell generates an outgoing as well as an inmoving shock which are clearly seen in Fig. 5, where the density distribution is presented. The payload density has been increased to about  $25 \text{ g/cm}^3$  due to the compression by the inmoving shock which is subsequently transmitted into the water region and reverberates between the cylinder axis and the water–tungsten boundary. In Fig. 6 we present the density distribution at  $t = 100 \text{ ns}$ . It is seen that the inner target radius has already been reduced which means compression of the water. The process of multiple shock reflection is seen in Fig. 7 where we plot the density vs radius at  $L = 3.5 \text{ mm}$  in the water region at different times. This multiple shock reflection scheme leads to a low–entropy compression of the sample material.

The compression results are shown in Figure 8–10 where we plot the density, the temperature and the pressure vs radius at  $L = 3.5 \text{ mm}$  in water at the time of maximum compression using different values of  $N$ , namely,  $5 \times 10^{11}$ ,  $3 \times 10^{11}$  and  $10^{11}$  ions per bunch, respectively. It is seen in Fig. 8 that the radius of the water region has been reduced to  $75 \mu\text{m}$  from an initial value of  $200 \mu\text{m}$ . The water density is about  $7 \text{ g/cm}^3$  while the temperature within the inner  $20 \mu\text{m}$  is high that corresponds to a plasma state. In the outer part, however, the temperature is below  $7000 \text{ K}$  and the pressure is of the order of  $15 \text{ Mbar}$ , that corresponds to a superionic state of water in which the protons are mobile in an oxygen lattice [6]. The following figures show that as the beam intensity decreases, the density, the temperature as well as the pressure in the compressed water decrease and the region in which the superionic phase exists, increases. Fig. 10 shows that in case of  $N = 10^{11}$  ions per bunch, the maximum density is  $4.5 \text{ g/cm}^3$ , the maximum pressure is about  $4 \text{ Mbar}$  while the average temperature is of the order of  $3000 \text{ K}$  and the entire sample is in a superionic phase.

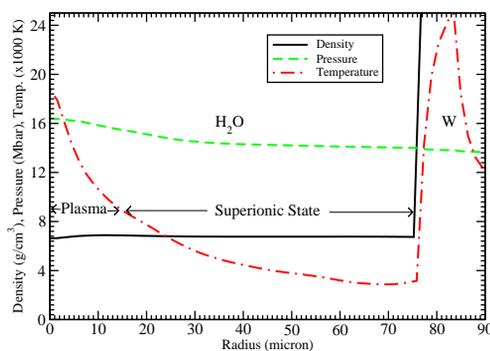


Figure 8: Density, temperature and pressure vs radius at time of maximum compression for a beam intensity,  $N = 5 \times 10^{11}$  ions per bunch.

## CONCLUSIONS

Simulations presented in this paper demonstrate that intense particle beams are an efficient tool to implode a sample material to generate physical conditions that are ex-

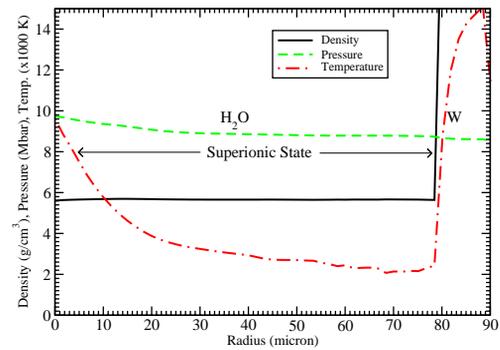


Figure 9: Same as in Fig. 8, but using  $N = 3 \times 10^{11}$  ions per bunch.

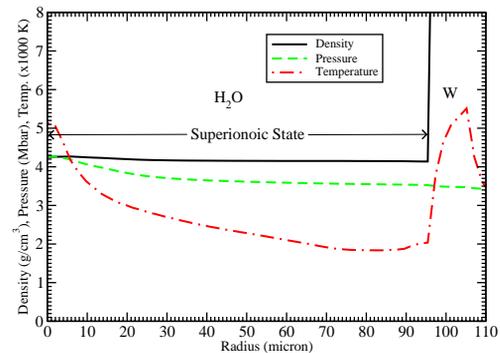


Figure 10: Same as in Fig. 8, but using  $N = 10^{11}$  ions per bunch.

pected to exist in the interiors of the giant planets. In this study we consider water as the sample material which presumably is abundant in Neptune–like planets. This study has shown that it is possible to achieve the plasma phase as well as the superionic phase of water in the proposed LAPLAS experiments.

## ACKNOWLEDGMENTS

The authors wish to thank the BMBF, DFG within the SFB 652 and the grant RE 882/11, HLRN via grant mvp–00001, the RFBR grant No.08-02-92882-NNIO-a, Russia, Ministerio de Ciencia Innovacion (ENE2009-09276) and Consejeria de Ciencia Tecnologia of Spain (PAI08-0152-7994) for providing the financial support for this work.

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