High Energy Density Physics Research Using Intense Heavy Ion Beam at FAIR: The HEDgeHOB Program

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Abstract. International project, Facility for Antiprotons and Ion Research (FAIR), has entered in its construction phase at Darmstadt. It is expected that the new powerful heavy ion synchrotron, SIS100 will deliver a strongly bunched intense beam of energetic uranium ions that will provide the scientists with an efficient and novel tool to research High Energy Density (HED) Physics in the laboratory. Over the past 15 years, substantial theoretical work has been done to design numerous experiments that can be done at this facility in this field. This work has resulted in an extensive scientific proposal named HEDgeHOB, that includes experiment proposals addressing various aspects of HED matter, for example, planetary physics, equation of state, hydrodynamic instabilities and others. In this paper we present a summary of this work.

1. Introduction

Due to its wide applications to numerous branches of basic and applied physics, High Energy Density (HED) physics is one of the most active research fields worldwide. Static as well as dynamic schemes have been employed over the past many decades for this purpose. The most popular static technique involves compression of a small sample of material in a diamond anvil cell to generate HED states. Dynamic schemes, on the other hand, rely on shock compression to induce HED stases in matter. Traditionally, shocks are produced by high power chemical explosives, gas guns, high power lasers and magnetic devices. Recent developments and expected progress in the near future in the technology of strongly bunched, well focused and energetic high intensity ion beams have provided the scientists with a novel, very efficient tool to study HED physics [1, 2].

It is to be noted that one may generate HED matter using two alternative dynamic methods, namely isochoric heating and shock compression of the material. It is also important to note that particle beams offer great flexibility as they can be used in both type of schemes whereas all other drivers are only suitable for either of the two methods.

The facility for Antiprotons and Ion Research (FAIR) at Darmstadt, has entered into construction phase that includes the building of a new very powerful heavy ion synchrotron, SIS100. According to the design parameters, the SIS100 beam will comprise of 5×10^{11} uranium ions that will be delivered in 50 ns long bunch. A flexible particle energy range (400 eV/u – 2.7 GeV/u) will be available while the beam can be focused to a spot size characterized with a

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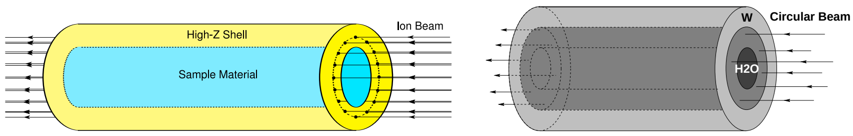

(a) (b)

Figure 1. LAPLAS experimental scheme, (a) driven by annular focal spot; (b) driven by a circular focal spot.

full width at half maximum (FWHM) = 1 mm. Provisions have also been made to generate an annular focal spot to do compression experiments.

Over the past 15 years, substantial theoretical work that includes sophisticated two– and three–dimensional numerical simulations as well as analytic modeling, has been done to design HED physics experiments at FAIR. This work has resulted in a very wide range experimental scientific program named, HEDgeHOB for FAIR. A brief overview of this program is presented in this paper.

2. High Energy Density Physics and Planetary Science Research at FAIR

HEDgeHOB includes different experiment proposals that consider isochoric heating technique as well as shock compression mechanism to generate samples of HED matter in the laboratory. The former technique is employed in the HIHEX (Heavy Ion Heating and EXpansion) experiment that has been designed to study the Equation of State (EOS) properties of HED matter [2]. The latter technique has been used in the LAPLAS (LAboratory PLAnatery Science) experiment design [3, 4] as well as for hydrodynamic instability studies [5]. In this section we present recent theoretical studies using the LAPLAS scheme.

The two configurations of the LAPLAS experiment are shown in Fig. 1(a) and (b), respectively. In the first case the target is driven by a hollow beam with an annular focal spot, whereas is the latter scheme, a circular focal spot is used to implode the target. In case of an annular focal spot, the sample material is not directly heated by the beam because the energy is deposited in the surrounding shell that leads to very high pressure. This high pressure launches a strong shock radially inwards that reflects at the cylinder axis and then re-verbrates between the axis and the boundary between the sample and the outer shell, thereby leading to a low–entropy compression. Simulations have shown that using the SIS100 beam parameters, hydrogen can be compressed to about 2 – 3 g/cm^3 having temperature in the range of 10000 – 20000 K and pressure up to about 30 MBar. These are the conditions that are expected to exist in the interior of Jupiter and other hydrogen rich exo-planets. In case of a circular focal spot, on the other hand, the sample material is also directly heated by the beam. However, due to the much higher pressure in the surrounding shell, the sample is still strongly compressed, although the final temperature in this case is higher. Further details about compression of hydrogen can be found in [6].

Considering both LAPLAS configurations, detailed two–dimensional hydrodynamic simulations have been carried out to study compression of water which is abundant in Uranus and Neptune as well as in similar water rich exoplanets. Figs. 2(a) – (c), show the density, temperature and pressure vs target radius in the compressed water region using 10^{11}, 3×10^{11} and 5×10^{11} ions per bunch, respectively, for an annular focal spot. It is seen that the physical conditions in the sample material correspond to the theoretically predicted [7] superionic phase of water. In Fig. 2(d) we show the regions of the phase diagram of water that can be accessed

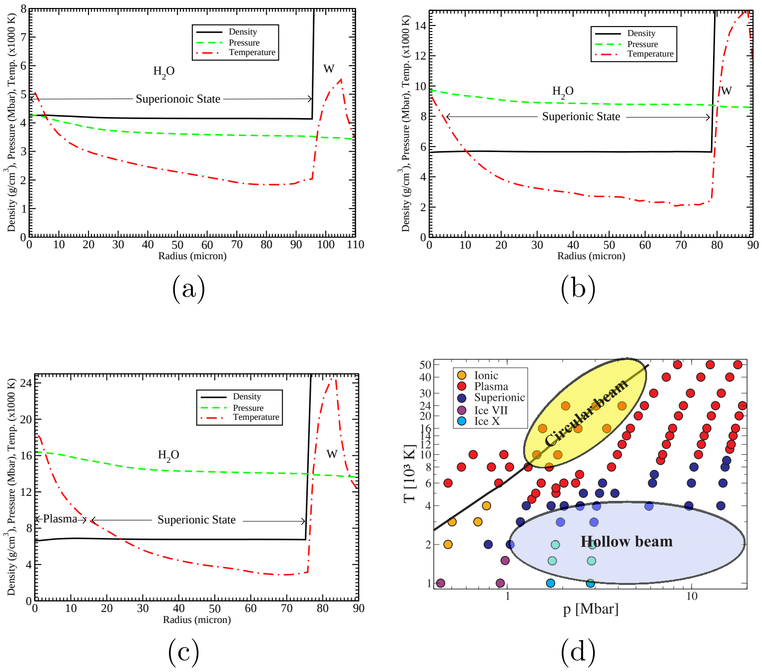

Figure 2. (a) ρ, T and P vs radius in compressed water using 10^{11} ions per bunch; (b) using 3×10^{11} ions per bunch; (c) using 5×10^{11} ions per bunch and (d) shows regions of water phase diagram [7] that can be accessed by the two LAPLAS schemes respectively.

at the FAIR facility in the LAPLAS experiments. It is seen that the superionic phase can only be accessed using an annular focal spot because in case of a circular focal spot, water is directly heated by the beam and the final temperature is higher. In this case one can generate plasma state of water. Further details can be found in [4].

Equation of state of iron under extreme conditions of density and pressure is also of great relevance to planetary physics as the earth core is made of solid iron. The discovery of huge earthlike extrasolar solid planets, named "superearths" or "exoearths" have made study of this problem much more important. The pressure in the earth's solid core is believed to be about 3 MBar, whereas it is expected that the pressure in the core of larger extrasolar earthlike planets could be as high as 10 MBar. In order to generate these extreme conditions, we have done simulations of compression of solid iron in the LAPLAS scheme considering an annular focal spot using the SIS100 uranium beam. The results are presented in Figs. 3(a) – (e). Fig. 3(a) shows the temperature, pressure and density vs radius in the compressed iron for a beam intensity of 10^{11} ions per bunch. It is seen that iron is compressed to 50 % higher than the solid density while a pressure of 2 MBar is achieved. The temperature is relatively low (650 K). In Fig. 3(b) we plot the same variables as in Fig. 3(a), but using a beam intensity of 2×10^{11} ions per bunch. In this case the compression is 75 % higher than the solid density while the pressure is around 4 MBar and the temperature is about 900 K. Fig. 3(c) shows that using a beam intensity of 3×10^{11} uranium ions per bunch, the compression is 87 % above the solid density, the temperature is about 1000 K whereas the pressure is above 5 MBar. Figs. 3(d) and (e) show that using higher intensities, iron can be compressed to twice the solid density and pressure as high as 8 MBar can be achieved. This shows that LAPLAS experiments can generate wide range of extreme physical conditions in iron relevant to the structure of a variety of solid earthlike planets. It is also imortant to study LAPLAS implosion of iron using a circular

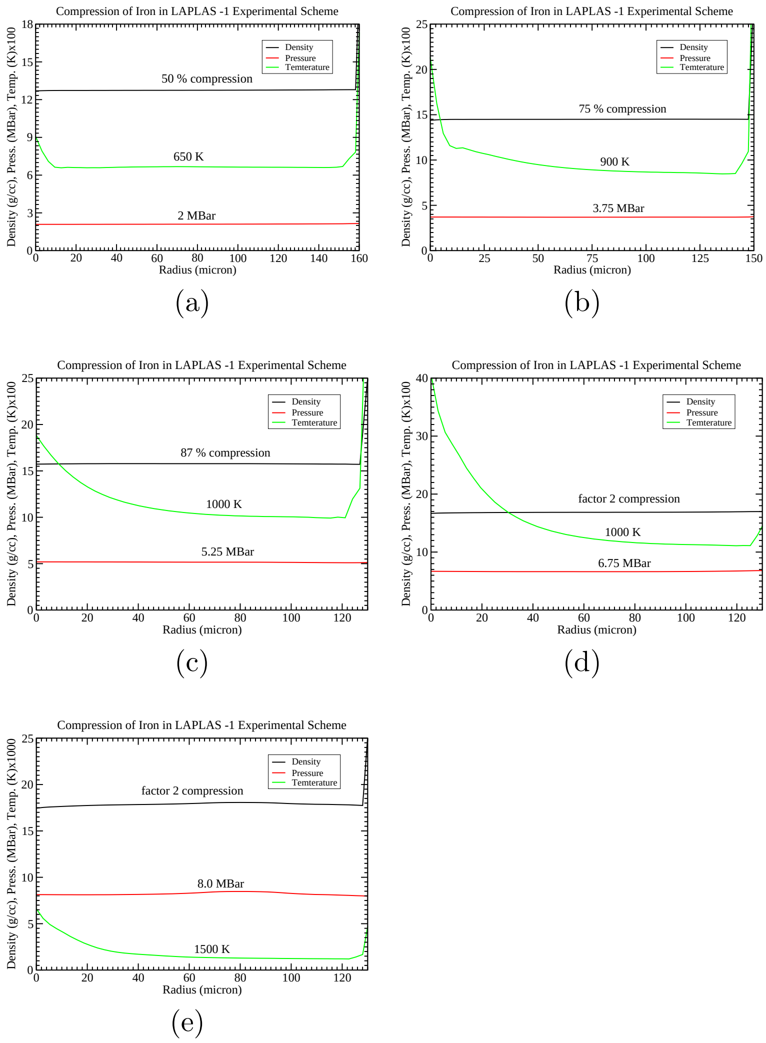

Figure 3. ρ, T and P vs radius in compressed iron (a) using 10^{11} ions per bunch; (b) using 2×10^{11} ions per bunch; (c) using 3×10^{11} ions per bunch; (d) using 4×10^{11} ions per bunch and (e) using 5×10^{11} ions per bunch

focal spot in order to generate higher temperatures. This work is in progress.

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