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The creation of strongly coupled plasmas using an intense heavy ion beam: low-entropy compression of hydrogen and the problem of hydrogen metallization

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Abstract

Intense heavy ion beams deposit energy very efficiently over extended volumes of solid density targets, thereby creating large samples of strongly coupled plasmas. Intense beams of energetic heavy ions are therefore an ideal tool to research this interesting field. It is also possible to design experiments using special beam–target geometries to achieve low-entropy compression of samples of matter. This type of experiments is of particular interest for studying the problem of hydrogen metallization.

In this paper we present a design study of such a proposed experiment that will be carried out at the future heavy ion synchrotron facility SIS100, at the Gesellschaft für Schwerionenforschung, Darmstadt. This study has been done using a two-dimensional hydrodynamic computer code. The target consists of a solid hydrogen cylinder that is enclosed in a thick shell of lead whose one face is irradiated with an ion beam which has an annular (ring shaped) focal spot. The beam intensity and other parameters are considered to be the same as expected at the future SIS100 facility. The simulations show that due to multiple shock reflection between the cylinder axis and the lead–hydrogen boundary, one can achieve up to 20 times solid density in hydrogen while keeping the temperature as low as a few thousand K. The corresponding pressure is of the order of 10 Mbar. These values of the physical parameters lie within the range of theoretically predicted values for hydrogen metallization.

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We have also carried out a parameter study of this problem by varying the target and beam parameters over a wide range. It has been found that the results are very insensitive to such changes in the input parameters.

PACS numbers: 51.50.+v, 25.75.−q, 62.50.+p, 79.20.Rf

1. Introduction

It has been shown with the help of two-dimensional hydrodynamic simulations that the heavy ion beam which will be generated at the existing heavy ion synchrotron facility, SIS18, after completion of its upgrade and that generated at the future SIS100 facility, at the Gesellschaft für Schwerionenforschung (GSI), will create fairly large samples of high-energy-density (HED) matter including strongly coupled plasmas [1–3]. Such samples can be used to study the equation-of-state (EOS) properties of these exotic systems in the laboratory. In particular, the EOS of hydrogen is of great scientific interest as hydrogen is the most abundant element in the universe. For instance, to model the interior of the giant planets one needs to know the properties of hydrogen under conditions of ultra high pressure and density. Moreover, the possibility of transformation of normal molecular hydrogen, which is an insulator, to an atomic metallic state when subjected to very high pressures [4], is an intriguing problem which has fascinated generations of physicists. Extensive experimental work has been done during the past decades to compress samples of hydrogen using static high pressures generated in a diamond anvil cell [5, 6] as well as dynamic pressures produced by different generators including gas gun, high power laser and high power explosives [7–10].

In the original paper by Wigner and Huntington [4], a pressure of 0.25 Mbar was predicted for an insulator-to-metal transition in hydrogen. Although pressures of the order of 3 Mbar have been achieved to date in the different experiments mentioned above, this long awaited transition in solid hydrogen has not yet been observed. However, useful information about some important aspects of the EOS properties of hydrogen under extreme conditions of density and pressure has been obtained, for instance, the transition of insulator hydrogen to a good conductor [7].

In a previous paper [11] we demonstrated with the help of two-dimensional hydrodynamic simulations that an intense heavy ion beam could be an additional and more efficient tool to study this problem. It was also shown that this scheme may have a number of advantages over other traditional schemes. The beam–target geometry for this proposed experiment is shown in figure 1. It is seen that the target is composed of a solid hydrogen cylinder with a radius R_{h0} which is enclosed in a thick shell of solid lead. The right face of the target is irradiated with an ion beam which has an annular focal spot. The inner radius of the focal ring, R_1, is assumed to be larger than R_{h0} which avoids direct heating of the hydrogen. The outer radius of the focal spot ring, R_2, is considered to be much less than that of the lead shell, R_e. The region $R_2 \leqslant r \leqslant R_e$ acts as a tamper that limits the outward expansion of the absorption region.

The high pressure in the absorber generates a shock wave which travels through the payload and is then transmitted into the hydrogen. This shock travels along the radius of the hydrogen cylinder and is reflected at the axis. The reflected shock travels outward and is re-reflected by the payload. This process of multiple shock reflection goes on while the payload continues to move inwards, slowly compressing the hydrogen. This leads to a low entropy or ‘cold compression’ of the hydrogen layer. First numerical simulations have shown [11] that using appropriate beam and target parameters, one can easily achieve the theoretically

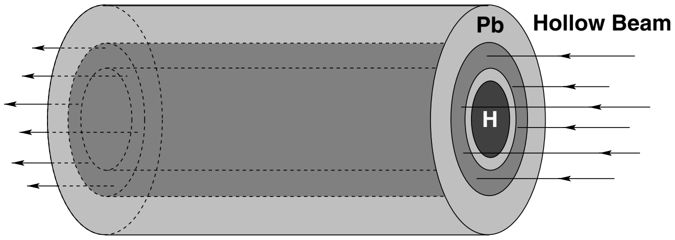

Figure 1. Target initial conditions.

predicted physical conditions necessary for hydrogen metallization. These include a density of about 1 g cm^{-3}, a pressure of the order of 5 Mbar and a temperature of a few thousand K.

In order to supplement the simulation studies, a sophisticated one-dimensional analytic model to study ion beam driven implosion of a multi-layered target such as the one shown in figure 1 has recently been developed [12]. This model successfully describes the target dynamics during different stages of the implosion and predicts that the physical conditions of the compressed hydrogen are not sensitive to significant variations in beam and target geometry. These predictions have been confirmed with one-dimensional numerical simulations.

The above analytic model has proved very helpful in further studying this problem using a sophisticated two-dimensional hydrodynamic computer code, BIG-2 [13], and the results of this study are reported in the present paper. In section 2 we briefly discuss the future heavy ion synchrotron facility, SIS100, to be built at the GSI Darmstadt. The target and beam parameters used in this study are noted in section 3. The simulation results are presented in section 4 while conclusions drawn from this work are given in section 5.

2. Future SIS100 facility at the GSI Darmstadt

The GSI Darmstadt is planning to significantly extend its accelerator facilities by building a new synchrotron ring, SIS100, which will have a maximum magnetic rigidity of 100 T m. Preliminary design studies show that this facility will deliver an intense uranium beam having a maximum number of 2 × 10^{12} ions which will be delivered in a single bunch. A wide range of particle energy (400 MeV u^{-1}–2.7 GeV u^{-1}) will be available while the bunch length corresponding to this particle energy range will be 90–20 ns respectively. It is expected that the beam will be focused to a small spot having a diameter of the order of 1 mm. It is also being planned at the GSI to design and construct a high frequency RF wobbler that will generate the annular focal spot required for the experiment discussed in the present paper.

3. Beam and target parameters

In this study we consider a particle energy of 2.7 GeV u^{-1} and a pulse length of 20 ns. The target length is assumed to be 1.0 cm. The range of 2.7 GeV u^{-1} uranium ions in solid cold lead [14] is 5.95 cm which will lead to a uniform energy deposition.

We assume two values for the hydrogen mass m_h, namely 0.5 mg cm^{-1} and 2.0 mg cm^{-1}. For each of these two cases we consider six different values of the payload mass m_{pl} including 25 mg cm^{-1}, 50 mg cm^{-1}, 75 mg cm^{-1}, 100 mg cm^{-1}, 125 mg cm^{-1} and 150 mg cm^{-1}. While changing the payload mass, we arrange R_1 and R_2 in such a manner that the area of the focal spot (ring) remains constant which leads to the same specific energy deposition in all different cases.

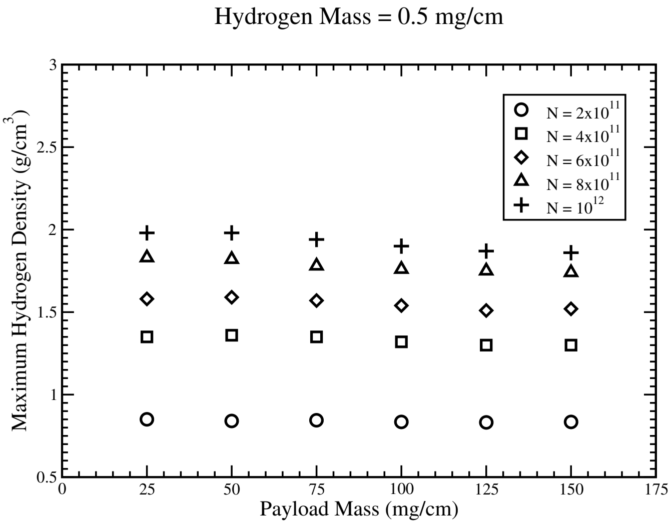

Figure 2. Maximum density in the compressed hydrogen versus payload mass for different values of beam intensity, using a hydrogen mass = 0.5 mg cm^{-1}.

The beam intensity is expected to increase gradually over a period of a few years. We therefore consider different beam intensities (total number of particles in the bunch, N), in the range $N = 10^{11}$–10^{12}.

4. Simulation results

In this section we present the numerical simulation results of the implosion of the target shown in figure 1 considering the beam parameters given in section 3. These simulations have been carried out employing a two-dimensional hydrodynamic computer code, BIG-2 [13].

First we consider the case when $m_h = 0.5$ mg cm^{-1} which means $R_{h0} = 0.424$ mm. Keeping the hydrogen mass constant, we have done calculations using different values of the payload mass, $m_{\rm pl} = 25$ mg cm^{-1}, 50 mg cm^{-1}, 75 mg cm^{-1}, 100 mg cm^{-1}, 125 mg cm^{-1} and 150 mg cm^{-1}. For $m_{\rm pl} = 25$ mg cm^{-1} we have $R_1 = 0.50$ mm and we consider $R_2 = 1.5$ mm which leads to an absorber mass (material that lies between R_1 and R_2) $m_a = 712$ mg. To keep the specific energy deposition constant, we keep the absorber mass the same for all the above cases and thus evaluate the corresponding value of R_2 in each case. Moreover, we consider five different values for the beam intensity with $N = 2 \times 10^{11}, 4 \times 10^{11}, 6 \times 10^{11}, 8 \times 10^{11}$ and 10^{12} respectively. These values of beam intensity lead to a specific energy deposition of 7.3 kJ g^{-1}, 14.6 kJ g^{-1}, 21.9 kJ g^{-1}, 29.2 kJ g^{-1} and 36.5 kJ g^{-1} respectively. The results are shown in figures 2 and 3 where we plot the maximum density and maximum pressure achieved in hydrogen versus payload mass for the above values of the beam intensity. It is seen that the results are very insensitive to large variation in the payload mass as predicted by the analytic model [12]. This implies that the target can tolerate very large uncertainties in the beam and target geometry which leads to a very robust design. Moreover, figures 2 and 3 show that the above beam intensity range leads to a hydrogen density of 0.8 g cm^{-3}–2.0 g cm^{-3} and a corresponding pressure of 2 Mbar–10 Mbar. The temperature of the sample lies between 1000 K–5000 K. This is a very interesting regime of the physical conditions as the insulator-to-metal transition in hydrogen is expected to lie in this region.

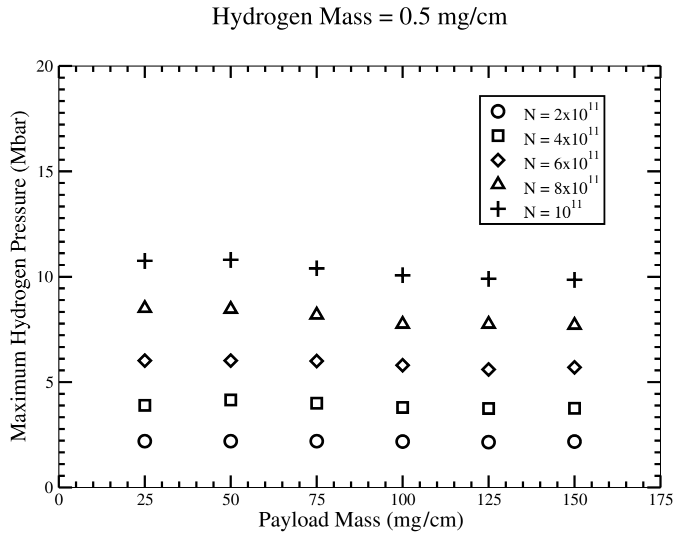

Figure 3. Maximum pressure in the compressed hydrogen versus payload mass for different values of beam intensity, using a hydrogen mass = 0.5 mg cm^{-1}.

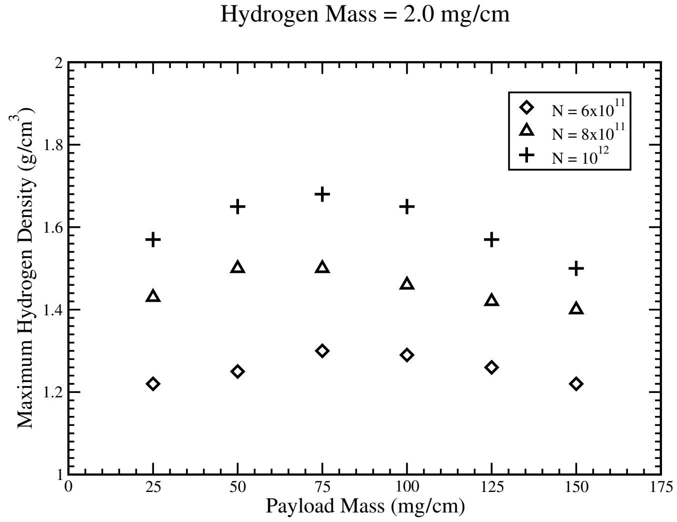

Figure 4. Same as in figure 2, but using a hydrogen mass = 2.0 mg cm^{-1}.

We have also carried out calculations using a much bigger hydrogen mass of 2.0 mg cm^{-1}, while keeping the rest of the conditions the same as in the previous case except that we use only three values of the beam intensity. The results are shown in figures 4 and 5. It is seen that unlike the previous case, the density and pressure slightly peak around $m_{\mathrm{pl}} = 75$ mg cm^{-1}. Moreover, the final density and the final pressure values are somewhat less than those achieved in the corresponding previous cases using $m_h = 0.5$ mg cm^{-1}. The main advantage of using a larger hydrogen mass is that the final radius of the compressed hydrogen sample is larger, which would make the diagnostics easier.

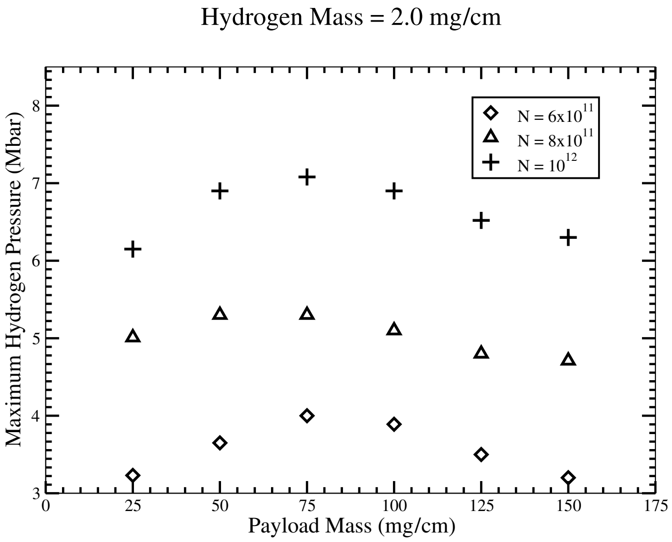

Figure 5. Same as in figure 3, but using a hydrogen mass = 2.0 mg cm^{-1}.

5. Conclusions

We have shown with the help of two-dimensional simulations that it is possible to use an intense heavy ion beam to achieve a 'low entropy' or cold compression of a test material such as hydrogen that is enclosed in a thick metallic shell. The beam parameters used in this study are considered to be those which are expected to be available at the future SIS100 facility at the GSI Darmstadt. This study shows that the results are very insensitive to significant variations in the beam and the target geometry which allows for a very robust target design.

Acknowledgments

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