Intense heavy ion beams as a tool to induce high-energy-density states in matter


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Because of the volume character of energy deposition of energetic ions in matter, an intense heavy ion beam is a very suitable laboratory tool to create large samples of high-energy-density matter. This paper shows with the help of two-dimensional numerical simulations how such an intense heavy ion beam can be employed to achieve this goal. The beam parameters considered in this study are those of the beams that are delivered by the existing heavy ion synchrotron, SIS18 and that which will be available at the future facility SIS100, respectively at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt.

1 Introduction

An intense heavy ion beam may be employed to study the field of high-energy-density (HED) matter using two different schemes. In first scheme one may use the volume character of energy deposition of energetic heavy ions in matter to heat the target quasi-isochorically and then allow this heated matter to expand isentropically. While going through the expansion phase, the heated matter will pass through different important physical states. For example, if one starts with a solid target, it will transform into an expanded hot liquid which will subsequently approach two-phase liquid-gas region. One could also access the very interesting critical point region. If on the other hand, one deposits sufficiently large specific energy in the target, the material would become a strongly coupled (non-ideal) plasma. All these matter states have not yet been thoroughly investigated and we believe that an intense heavy ion beam will be an additional tool to study this field [1].

In the present paper we present two-dimensional numerical simulations of isochoric heating of cylindrical zinc targets with a uranium beam. In this study we have considered the beam parameters that will be available at the heavy ion synchrotron facility, SIS18 at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt in the near future.

The second proposed scheme considers low entropy compression of a sample material like frozen hydrogen that is enclosed in a multi-layered target and that is imploded by an ion beam which has an annular or a ring shaped focal spot. Numerical simulations [2] and analytic studies [3] have shown that using such a scheme one may access theoretically predicted physical conditions necessary to achieve hydrogen metallization. These include a density of 1-2 g/cm³, a pressure of 3-10 Mbar and a temperature of a few thousand K. The beam

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parameters were considered to be that of the beam that will be generated at the future SIS100 facility at the GSI. It has also been shown[4] that an annular focal spot can be generated using an rf-wobbler that rotates the beam with a high frequency of the order of a GHz. In this paper we report calculations using two different equation-of-state (EOS) models for hydrogen, namely the SESAME data [5] and a molecular dissociation model [6] which is supplemented with Padé approximation for the plasma region [7].

2 Simulation Results

In this section we present numerical simulation results of the two heavy ion matter interaction schemes mentioned in the previous section. These simulations have been carried out using a two-dimensional hydrodynamic code, BIG-2[8].

2.1 Isochoric Heating of Matter

In this study we consider a cylindrical target that is made of solid zinc and which has a radius of 300 micron and has a length of 2 mm. This target is irradiated by a uranium beam along the length. The beam intensity (total number of particles, N) is assumed to be $10^{10}$ and the particle energy is 500 MeV/u. These particles are delivered in a single bunch which has a duration of 300 ns. The beam power profile along the radial direction is considered to be Gaussian with a full width at half maximum (FWHM) of 1 mm. It is expected that these beam parameters will be available at the SIS18 facility by the end of 2003.

It is to be noted that the target radius is much less than the FWHM of the intensity function along the radial direction. This will lead to a fairly uniform energy deposition along the target radius. Moreover according to the SRIM code [9] which is based on a cold stopping model for ions in matter, the range of 500 MeV/u uranium ions in solid zinc is about 7 mm, which is much longer than the target length. Therefore the energy deposition along the target length will also be uniform. The specific energy deposition in this case is 1.9 kJ/g. We note that with such moderate beam intensities the target temperature is not too high and the degree of ionization in the target is low so that the cold stopping model is a good approximation for this regime.

In Fig.1 we plot the target temperature on a length-radius plane at $t = 200$ ns. It is seen that the target is heated to a temperature of about 3500 K and also the target has expanded in the radial direction from an initial position of $r = 300$ micron to an $r = 400$ micron. As a result of this expansion the target density has decreased from an initial value of 7.13 g/cm$^3$ to 4.8 g/cm$^3$ as shown in Fig.2.

Figure 3 shows the state of the target material at $t = 200$ ns. It is seen that the bulk of the target material exists in the state of an expanded hot liquid at this time.
Figure 4 shows the target temperature, density and pressure vs radius at L = 1.0 mm (middle of the target) at t = 300 ns. It is seen that the temperature is of the order of 3100 K, the pressure is about 3 kbar while the density is 2.5 g/cm$^3$. These are the respective physical parameters corresponding to the critical point for zinc.

![Material State](image1)

**Fig. 3** Physical state of the target material at t = 200 ns.

![Density, Pressure, Temperature vs Radius](image2)

**Fig. 4** Density, pressure and temperature vs radius at L = 1 mm and at t = 300 ns.

In Table 1 we present the calculated physical parameters for different metals corresponding to their respective critical point regions. Our simulations have shown that using the above beam parameters one can easily access the critical point regions for these different materials. One may therefore study this interesting unexplored region using the ion beam that will be available at the GSI in the near future.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (K)</th>
<th>Pressure (kbar)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>5500</td>
<td>2.30</td>
<td>3.10</td>
</tr>
<tr>
<td>Gold</td>
<td>8500</td>
<td>6.14</td>
<td>6.10</td>
</tr>
<tr>
<td>Zinc</td>
<td>3080</td>
<td>3.30</td>
<td>2.40</td>
</tr>
<tr>
<td>Copper</td>
<td>7800</td>
<td>9.00</td>
<td>2.28</td>
</tr>
</tbody>
</table>

### 2.2 Compression of Hydrogen

Equation-of-state of hydrogen under extreme physical conditions is of considerable importance to astrophysics and planetary sciences. In addition to that the prediction by Wigner and Huntington in 1935 that hydrogen may transform into a metal when subjected to extremely high pressures [10] made this field of research very important as metallized hydrogen is expected to have very lucrative industrial applications[11]. During the past few decades due to significant advancements in the high pressure technology, static [12] as well as transient [13-15] pressure schemes have been employed to compress samples of hydrogen. Significant progress has been made to study certain aspects of the EOS of hydrogen and deuterium under such extreme conditions, but the final goal of achieving metallized hydrogen has not yet been reached.

Previously, we demonstrated with the help of numerical simulations that an intense heavy ion beam can be a very efficient additional laboratory tool to study this problem [2]. The beam-target geometry is shown in Fig.5. Our simulations have shown that using the future SIS100 beam (N = $10^{11} - 10^{12}$), one can achieve density in the range of 0.8 - 2.0 g/cm$^3$, pressure in the range of 2 - 15 Mbar and a temperature of a few thousand K. In these simulations we used the SESAME EOS data for hydrogen. However laser driven shock compression experiments have shown significant deviations from the simulations obtained using the SESAME data. It is thus important
to compare the simulation results using different EOS models for hydrogen. We carried out simulations using another model that includes molecular dissociation for the neutral fluid region that is based on a fluid variational theory (FVT) [7] which is supplemented with Padé approximations [8] for the plasma region. The beam intensity is assumed to be $10^{11}$ ions that are delivered in a single bunch, 20 ns long, while the particle energy is 2.7 GeV/u. The inner radius of the lead cylinder is 0.4 mm and the outer radius is 3 mm and has a length of 1 cm. The inner radius of the focal spot ring is 0.6 mm and the outer radius is 1.6 mm. The results are plotted in Fig.6.

Since we do not have an EOS for the solid phase of hydrogen, we assumed that the initial density of hydrogen in the target was one tenth of the solid density (0.0088 g/cm$^3$) at room temperature. Figure 6 shows that the FVT+Padé EOS leads to more compressibility of hydrogen compared to the SESAME. This is because the former includes a better treatment for molecular dissociation and ionization.

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References