Heavy Ion-Beam Driven Isentropic Compression Experiments

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A new design for heavy-ion beam driven isentropic compression experiments is suggested and analysed. The proposed setup utilises the long stopping ranges and the variable focal spot geometry of the high-energy uranium beams delivered at the GSI Helmholtzzentrum für Schwerionenforschung and Facility for Antiproton and Ion Research accelerator centers in Darmstadt, Germany, to produce a planar ramp loading of various samples. In such experiments, the predicted high pressure amplitudes (up to 10 Mbar) and short timescales of compression (below 10 ns) will allow to test the time dependent material deformation phenomena at unprecedented extreme conditions.

PACS numbers: 62.50.-p, 64.60.A-, 52.50.Gj

Research carried out in astrophysics, planetary and material sciences seek a thorough understanding of the behavior of matter at high pressures. For example, the equation of state (EOS) of iron under pressures of 1–4 Mbar is crucial in order to determine the state of the Earth’s core [1, 2, 3]. EOS data around 0.1 Mbar is required to establish the state and the composition in Earth’s lower mantle [3, 4], while the dynamics of the processes in the mantle is considered to be dependent on the structural phase transformation kinetics [5]. The pursuit after materials for technological applications [6] also entails a detailed understanding of the kinetics of the high-pressure phase transitions. Modelling the physical processes during the projectile impact relevant to meteoroid protection and crater formation [7] requires the dynamical response of solids at ultrahigh strain rates. Hydrogen EOS at high pressures are especially important for understanding the structure and evolution of the hydrogen-bearing astrophysical objects such as the giant planets like Saturn and Jupiter [8, 9] as well as for the inertial fusion energy research [10, 11].

The technique of isentropic compression using ramp wave loading (RWL) [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23] allows one to sample EOS data along an isentrope up to several Mbar pressures, located on the phase diagram between the parameter regions accessible in diamond anvil cell [24, 25] and shock wave [26, 27] experiments. Unlike a shock wave experiment where a single point on a shock adiabat is obtained, in isentropic compression experiments a continuous set of data points is recorded and the solid state of a sample is ensured up to high pressures. RWL technique was also shown to be a more sensitive tool for studying the dynamics of ultrafast structural phase transformations than the shock-wave based [28, 29, 30] methods.

RWL has been demonstrated with different drivers, such as magnetic pulse loading using high-current pulsed power generators [12, 13, 14, 15, 16, 17, 18, 19, 20], high-power lasers [20, 21, 22, 23], and gas guns [18] or high explosives [19] using graded density impactors. The typical loading times with these drivers are 10 ns, 100 ns and 1 µs, respectively. In this Letter, a new scheme for planar isentropic compression experiments using an intense heavy ion beam as a driver is proposed and analysed. The long absorption range and the variable focal spot size and shape of energetic ion beams allows one to design isentropic compression experiments with fairly planar geometry. The beam parameters needed to generate pressures of up to 4 Mbar in aluminium and 7 Mbar in iron are well within the reach of the uranium beams that will be delivered at the new Facility for Antiproton and Ion Research (FAIR) which is being built in Darmstadt. The beam intensities needed to generate pressures ap-

![FIG. 1: Schematic of the experimental design. The ion beam with an elliptic focal spot propagates in $z$ direction. It heats the absorber slab along its surface. The depth of the beam inside the absorber, i.e. the distance between the beam’s axis and the inner surface of the slab is $\Delta r$. The target foil of thickness $d$ is placed parallel to the absorber at a distance $D$. Hatched areas represent the support washer used to and to coax the expanding absorber material. The velocity of the rear target surface is recorded using a line-imaging VISAR.](https://example.com/figure1.png)
TABLE I: Parameters of the experiments with Al [cases (a)-(d)] and Fe [cases (e)-(h)] targets (see Fig. 1). $E_0$ is the ion energy, $N_0$ is the number of ions per pulse, $\tau$ is the pulse duration, and $\Delta x \times \Delta y$ are the FWHM dimensions of the beam focal spot. The depth of the beam in the absorber is $\Delta r = 0.2 \text{ mm}$ in all the cases. All spatial dimensions listed are in millimeters.

|      | $E_0$ [GeV/u] | $N_0$ | $\tau$ [ns] | $\Delta x \times \Delta y$ | D | d |
|------|---------------|-------|--------------|-----------------------------|---|---|
| (a)  | 2.7 $10^{12}$ | 50    | 0.3 $\times$ 0.5 | 0.2                         | 0.1 |   |
| (b)  | 2.7 $10^{11}$ | 100   | 0.3 $\times$ 1.0 | 0.5                         | 0.1 |   |
| (c)  | 0.2 $10^{12}$ | 100   | 0.3 $\times$ 1.0 | 0.5                         | 0.1 |   |
| (d)  | 0.35 $10^{10}$ | 100   | 0.3 $\times$ 0.5 | 0.2                         | 0.2 |   |
| (e)  | 2.7 $10^{12}$ | 50    | 0.3 $\times$ 0.5 | 0.2                         | 0.1 |   |
| (f)  | 2.7 $10^{12}$ | 50    | 0.3 $\times$ 0.5 | 0.2                         | 0.05 |   |
| (g)  | 2.7 $10^{11}$ | 100   | 0.3 $\times$ 1.0 | 0.5                         | 0.1 |   |
| (h)  | 0.2 $10^{10}$ | 100   | 0.3 $\times$ 1.0 | 0.5                         | 0.075 |   |

The major benefit of the proposed experimental design as compared to other approaches for EOS measurement with heavy ion beams [31, 32] is twofold. Firstly, the EOS along a compression adiabat can be determined by measuring only one parameter — the rear surface velocity employing a line-imaging VISAR as the principal diagnostics. Secondly, this design does not rely on detailed knowledge of the beam-matter interaction processes like the stopping power, since the beam energy is not deposited into the sample directly [20] but is converted to the kinetic energy of the absorber material. In order to interpret and use the results of the experiment one therefore does not have to precisely measure

FIG. 2: Evolution of pressure and density for the case (b) of Table I. The dotted vertical lines indicate the location of the target front surface at different times. The phases of the process are: (1) $t = 59 \text{ ns}$ — the evaporated absorber material — lead is accumulating at the front surface of the aluminium sample; (2) $t = 78 \text{ ns}$ — the isentropic compression has started; (3) $t = 86 \text{ ns}$ — the accumulation continues; the compression wave reaches the rear surface of the sample before the shock wave has formed; (4) $t = 94 \text{ ns}$ — the motion of the rear surface of the target foil can be detected.
the transverse distribution of the beam intensity at the focal plane, which can be problematic for intense focused heavy ion beams. Moreover, the presented design has also an important advantage that the target is not being preheated by energetic secondary particles and projectile fragments produced during the interaction of the beam with the absorber material. Furthermore, this approach requires neither high accuracy of the beam-target alignment, nor good short-to-shot reproducibility of the beam parameters.

Parameters of the beam and the target geometries considered in this work are summarised in Table I. The cases (a), (e) and (b), (f) in the table correspond to the beam parameters of the SIS-100 synchrotron to be available at FAIR [38], the cases (c), (g) correspond to the beams that will be available after completion of the SIS-18 upgrade [39], and the cases (d), (h) correspond to the present SIS-18 beam available for high energy density physics experiments [37, 39]. A lead absorber slab of 400 µm thickness was considered for all the analysed cases. The geometric parameters of the target have been adjusted to guarantee the planarity of the ramp compression wave propagating in the $x$ direction for at least $y \leq \pm 50 \mu m$, and to ensure a shockless compression of the target. The planarity of the designed experiment justifies a one dimensional analysis using the 1D hydrodynamic simulation code [40].

The calculated histories of the pressure at the front and the velocity at the rear surfaces of the aluminium samples are shown in Fig. 3. The planarity of the compression wave can be adjusted by varying the ion beam extension in the $y$ direction. However, this also affects the level of specific energy density deposited by the beam in the absorber. Two possible beam cross sections are compared: in the case (a) the FWHM height of the beam spot is 0.5 mm, whereas in the case (b) — 1 mm. Increasing the height of the beam spot allows one to increase the vacuum gap which enhances the smoothness of the loading without loosing in the planarity. The curves corresponding to these two cases indicate that the enhancement of the smoothness of the loading compromises the amplitude of the compression: the maximum pressure corresponding to case (a) is about 3.5 Mbar, whereas in case (b) it is only about 2 Mbar. The maximum pressure that one can obtain using upgraded SIS-18 beam (c) is about 1 Mbar and the currently available SIS-18 beam (d) can isentropically load aluminium up to 500 kbar.

The strain rate is approximately $8 \times 10^7$ s$^{-1}$ at the peak pressure of about 2 Mbar in the examined case (b) (see Table I). The corresponding time to the maximum compression is approximately 20 ns, which is comparable to the rise time of low-stress steady shock [52]. The laser RWL experiments by Smith et al. [23] at similar compression times and strain rates have demonstrated a stiffening of the stress-strain response. Using ion beams, the adjustable ion pulse duration, focal spot size and the depth of the ion beam in the absorber allow a degree of control over the compression time, amplitude and strain rate. This provides a unique tool to carry out parametric studies of the stress-strain response.

A similar analysis has been carried out for iron samples (Table I). The corresponding histories of the front face pressure and rear face velocity are shown in Fig. 4. One can see that a Mbar pressure loading is within the reach of the existing SIS-18 beam, whereas the upgrade of the machine can provide the compression data of up to about 3 Mbar in the nearest future. Up to 6 Mbar pressures will be generated in the corresponding experiments at FAIR with extremely high strain rates of the order of $10^8$ s$^{-1}$.

The curves (e) and (f) in Fig. 3 demonstrate the differences between the velocity traces in case of shock and adiabatic compression, respectively. In order to ensure shockless loading, the sample’s thickness had to be reduced from 100 µm as in the case (e) to 50 µm as in the case (f). Obviously, decreasing the sample’s thickness causes the motion of the sample’s rear surface to start earlier. This motion acts to release the pressure of the absorber’s material piling up at the front surface of the sample and to reduce the pressure amplitude in the target. Therefore, a compromise should be devised to ensure the adiabatic character of the compression on one side, and to obtain the highest possible pressure on the other.

The capabilities of the high-energy heavy ion beam accelerators available at GSI and later at FAIR to drive planar isentropic compression of solids were analysed. It was shown that the time scales of the loading are comparable with the fastest laser drives [20, 23], and the amplitudes of pressure surpass those obtained using the high-power magnetic drives [17]. These features allow to
investigate the dynamical response of solids in the regime of previously unattainable parameters and possibly the dynamics of the pressure-induced structural phase transformations [28, 29, 30]. Moreover, ramp loading with pressures higher than 0.1 Mbar can be obtained in multilayer targets [30] using the currently existing SIS-18 ring for the purpose of studying the pressure induced phase transformations in water.

Support from EPSRC and INTAS is gratefully acknowledged.

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