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Proposed studies of strongly coupled plasmas at the future FAIR and LHC facilities: the HEDgeHOB collaboration

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Abstract

Detailed theoretical studies have shown that intense heavy-ion beams that will be generated at the future Facility for Antiprotons and Ion Research (FAIR) (Henning 2004 *Nucl. Instrum. Methods* B **214** 211) at Darmstadt will be a very efficient tool to create high-energy-density (HED) states in matter including strongly coupled plasmas. In this paper we show, with the help of two-dimensional numerical simulations, the interesting physical states that can be achieved considering different beam intensities using zinc as a test material. Another very interesting experiment that can be performed using the intense heavy-ion beam at FAIR will be generation of low-entropy compression of a test material such as hydrogen that is enclosed in a cylindrical shell of a high-Z material such as lead or gold. In such an experiment, one can study the problem of hydrogen metallization and the interiors of giant planets. Moreover, we discuss an interesting method to diagnose the HED matter that is at the centre of the Sun. We have also carried out simulations to study the damage caused by the full impact of the Large Hadron Collider (LHC) beam on a superconducting magnet. An interesting outcome of this study is that the LHC beam can induce HED states in matter.

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1. Introduction

There has been considerable interest in the development of technology of bunched, highly energetic, intense particle beams in recent years. Two such facilities are under construction, one at Darmstadt, which is named FAIR (Facility for Antiprotons and Ion Research) [1] and the other at CERN, the LHC (Large Hadron Collider). FAIR includes construction of a heavy-ion synchrotron SIS100 that will accelerate strongly bunched intense particle beams from protons to uranium which will be used to carry out experiments in the fields of particle physics, nuclear physics, atomic physics and high-energy-density (HED) matter. For the HED matter experimental studies, the heaviest ions, uranium, are the most suitable as these ions lead to the highest energy deposition in matter. In order to construct the huge experimental facilities at the FAIR and later to carry out experiments in the field of HED states in matter, a very broad international collaboration that has attracted physicists from all over the world belonging to very disparate fields of interest has been formed. This collaboration has been named HEDgeHOB which stands for high-energy-density matter generated by heavy-ion beams.

The LHC, on the other hand, is a very powerful proton synchrotron which has a circumference of 26.7 km that is being constructed at CERN. It will generate two counter-rotating beams of highly relativistic protons (7 TeV energy) that will be made to circulate in separate pipes and then will be made to collide at a centre-of-mass energy of 14 TeV. Since the energy stored in each of the LHC beams is unprecedented, safety of operation is a very important issue. Simulation studies have been carried out to assess the damage caused by the full impact of one of the LHC beams on a solid copper target. An interesting outcome of this study is that such an impact would induce states of HED in matter.

In sections 2 and 3, we present calculations showing the potential of the FAIR facility and the LHC to carry out research in the field of HED matter, respectively. In section 4, we describe an experiment that can be used to diagnose the core of the Sun. Conclusions drawn from this work are noted in section 5.

2. High-energy-density matter studies using heavy-ion beams at FAIR

It is expected that when the heavy-ion synchrotron SIS100 is working at its full capacity at FAIR, it will deliver an intense uranium beam with an intensity $N = 2 \times 10^{12}$ ions that will be delivered in a single bunch, 50 ns long. A very wide range of particle energy, 400 MeV/u–2.7 GeV/u, will be available which will provide great flexibility in designing experiments. The beam focal spot (full width at half maximum (FWHM) of the transverse Gaussian intensity distribution) will have a radius of the order of 1 mm. Numerical simulations have shown that a beam with these parameters will deposit about 600 kJ g^{-1} specific energy in solid lead.

During the last few years, extensive theoretical work that includes sophisticated numerical simulations [2–12] and analytic modelling [13–15] has shown that an intense heavy-ion beam can be used employing two very different experimental schemes to study HED states in matter. The first scheme is named HIHEX which stands for heavy-ion heating and expansion, while the second is called LAPLAS that represents laboratory planetary sciences. In the following, we describe these two techniques in detail.

2.1. HIHEX technique

In this proposed experimental setup (see figure 2 in [8]), one considers a cylindrical target of a test material that is enclosed in a cylindrical shell of a mechanically strong material such as sapphire or LiF which is transparent to infrared, visible and ultraviolet radiation, with a small gap between the two. One face of the cylinder is irradiated by the ion beam that penetrates into the target. The range of the ions is assumed to be larger than the cylinder length and the beam radius is considered to be larger than the cylinder radius. This ensures uniform energy deposition along the particle trajectory and the radial direction. If the bunch length is shorter compared to the hydrodynamic response time of the material, the target will be heated isochorically. The heated material will then expand isentropically, passing through different interesting physical states. For example, it will become an expanded hot liquid, one can access critical point parameters, one can get into a two-phase liquid–gas region and if enough energy is deposited in the target, the solid target will be converted into a strongly coupled plasma. The function of the cylindrical wall of transparent material is to confine and homogenize the expanding hot material and to allow diagnostics during the experiment.

Using a two-dimensional computer code, BIG-2 [16], we simulated the hydrodynamic and thermodynamic response of solid zinc cylindrical targets irradiated by a uranium beam. We considered different values of the beam intensity, N, in the range 5×10^{10}–5×10^{11} ions per bunch, while the bunch length was 50 ns. The particle energy was assumed to be 1 GeV$/u$, and a circular beam spot with a diameter (FWHM of the Gaussian distribution) in the range 2–4 mm was considered. These simulations have shown that within the above range of beam parameters, one can easily access the critical parameters for zinc, namely $T_c = 3080$ K, $\rho_c = 2.4$ g cm^{-3} and $P_c = 3.3$ kbar [17]. In addition, one can generate a strongly coupled plasma with a coupling parameter Γ of up to 4.

We note that the critical temperature for most metals has not been measured experimentally because the estimated values of T_c for most of the metals are very high (tens of thousands of K) and cannot be accessed by traditional shock compression techniques. However, numerical simulations have shown that using our proposed HIHEX technique, one may easily generate the required temperature by depositing an appropriate amount of specific energy in the material. This underscores the power of this novel technique.

2.2. *LAPLAS scheme*

Hydrogen is the simplest and most abundant element in nature. The equation-of-state (EOS) of hydrogen at very high densities and ultra-high pressures is of considerable theoretical interest and is important for modelling planetary interiors. Static as well as dynamic schemes have been used to compress samples of hydrogen to create physical conditions that are expected to exist in the interiors of giant planets. The most popular static configuration used for this purpose is that of a diamond anvil cell (DAC) [18, 19]. Dynamic schemes involve shock compression of hydrogen using gas guns [20, 21], high-power lasers [22, 23] and high-power explosives [24]. Interest in this subject has increased manyfold due to the discovery of extrasolar giant planets.

According to our simulations, an intense heavy-ion beam can be an additional, very efficient tool to research this very interesting problem. In figure 1, we show the schematics of a proposed experiment that will allow one to compress material such as hydrogen or water to physical conditions that are similar to the interiors of the giant planets. This scheme resembles the previous experimental setup proposed to study the problem of hydrogen metallization [5]. In this latter scheme, it is necessary to use a beam with an annular focal spot that can be generated by an rf wobbler that will rotate the beam focal spot with a very high frequency of the order of a GHz [14]. In such a scheme, one face of the cylinder is irradiated by the beam and the ion range is considered to be larger than the cylinder length. Due to the annular shape of the focal spot, the hydrogen is not directly irradiated by the ion beam but the material in the gold shell around the hydrogen is heated. The high pressure in the heated region drives a

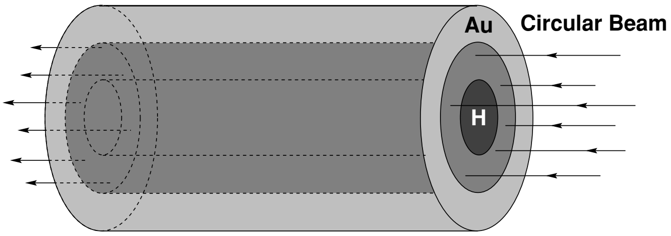

Figure 1. Proposed beam–target configuration for the LAPLAS scheme.

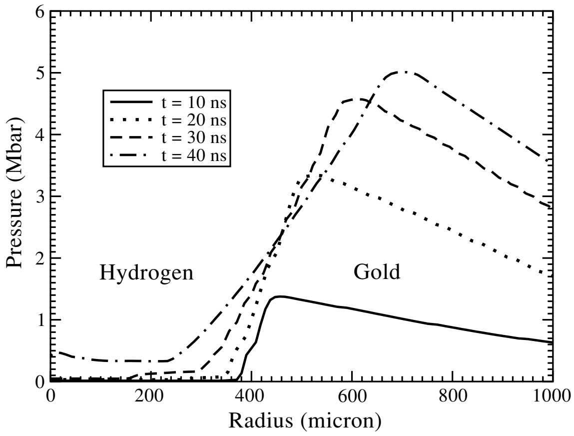

Figure 2. Pressure versus radius at $L = 5$ mm (middle of the cylinder), at different times, $N = 10^{12}$, $\tau = 50$ ns, energy = 2 GeV/u, FWHM = 1.5 mm, radius of hydrogen region = 0.4 mm.

shock that moves inwards along the radius that reverberates between the cylinder axis and the hydrogen–gold boundary, thereby leading to a low-entropy compression. Simulations predict [5, 6, 9] that in such experiments one would achieve a hydrogen density of 1–2 g cm^{-3}, a temperature of a few thousand K and a pressure between 5 and 15 Mbar. These are theoretically predicted physical conditions to metallize hydrogen.

In the present scheme, on the other hand, instead of using an annular focal spot, we consider a circular focal spot so that the beam heats the hydrogen and a part of the surrounding gold shell. Using the BIG-2 computer code, we have simulated implosion of the target shown in figure 1. The target length is 1 cm, the radius of the hydrogen region is 0.4 mm and the outer radius of the gold shell is 3 mm. The target is irradiated with a 2 GeV/u uranium beam having an intensity of 10^{12} ions per bunch with a bunch length of 50 ns. The beam spot is assumed to be circular with a FWHM of the Gaussian intensity distribution in the transverse direction (beam focal spot radius) = 1.5 mm.

Although the hydrogen is strongly heated by the beam, the pressure in the hydrogen is still orders of magnitude lower than that in the gold. This is seen from figure 2 where we plot the pressure versus radius at different times during the irradiation at a longitudinal position $L = 5$ mm (middle of the target). It is seen that at $t = 10$ ns the pressure in the gold region is of the order of 1 Mbar, while in hydrogen it is extremely low, although the temperature in the hydrogen region has increased from an initial value of 10 K to about 2000 K. This pattern

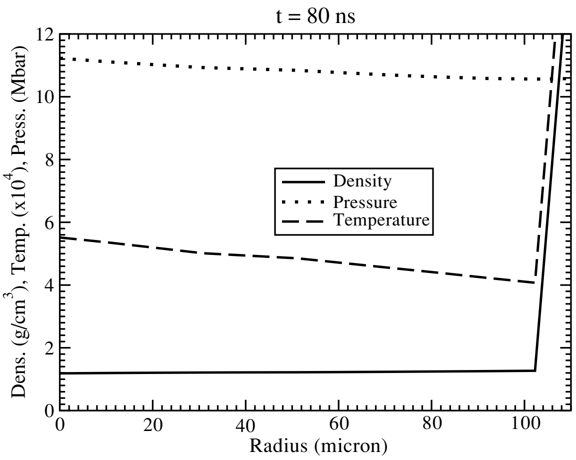

Figure 3. Density, temperature and pressure versus radius, at $L = 5$ mm (middle of the cylinder), at the time of maximum compression.

continues to exist till $t = 50$ ns when the beam has been switched off. Due to the large pressure gradient between the gold and the hydrogen region, the hydrogen is compressed to very high densities (1.2 g cm^{-3}), but in this case the temperature is much higher (a few eV) compared to the case when one uses an annular focal spot. The pressure in the hydrogen region is over 11 Mbar. This is seen from figure 3 where we plot the temperature, pressure and density in the hydrogen region versus cylinder radius at the middle of the target at the time of maximum compression (80 ns). These are the physical conditions that are expected to exist in the interior of Jupiter, Saturn and numerous extrasolar planets. One can therefore study the planet interiors in LAPLAS experiments at FAIR.

2.3. Diagnostics

Efficient diagnostics is the backbone to the success and usefulness of any experiment. In the proposed HIHEX scheme, the EOS will be determined by direct measurement of the basic physical parameters of the sample material including density, temperature and pressure. Due to the high density and exotic behaviour of the electrons in the HED sample, the standard diagnostic techniques will fail. Moreover, these exotic states are available in the laboratory in a highly transient state that requires a high temporal resolution of the diagnostics (typically of the order of a nanosecond).

For the temperature measurements, a fast multi-channel pyrometer is being developed. The large dynamic range (about 10 000) of this instrument due to its photodetectors, specially designed amplifiers and large number of channels will allow one to measure target temperatures over a wide range (from 1000 K to more than 60 000 K). The spatial resolution of the system will be as good as 50–100 μm which is sufficient to perform experiments using targets with typical dimensions of 1 mm.

Knowing the initial volume of the target, the density of the expanded material after achieving a steady state can easily be determined. Other methods that will be employed to determine the density distribution include ion and proton radiography. The ions will be provided by an additional diagnostic beam that will be delivered by the SIS18, while the protons will be generated by the Petawatt High-Energy Laser for Heavy-Ion Experiments (PHELIX) laser that is being constructed at the GSI. The ion and proton beams for radiography will be incident perpendicular to the target so that the W discs do not interfere with the measurements.

The expansion velocity of the material and the material pressure will be measured using laser interferometric methods, especially the VISAR technique [25].

3. High-energy-density matter studies using proton beams at LHC

The Large Hadron Collider (LHC) at CERN is being constructed to study fundamental problems in particle physics. The LHC will generate two counter-rotating proton beams with a particle energy of 7 TeV. Each beam will consist of 2808 bunches with an intensity per bunch of 1.15×10^{11} protons so that the total number of protons in one beam will be about 3×10^{14} and the total energy will be 362 MJ. Each bunch will have a duration of 0.5 ns and two successive bunches will be separated by 25 ns, while the power distribution in the radial direction will be Gaussian with a standard deviation $\sigma = 0.2$ mm. The total duration of the beam will be about 89 μs.

The two beams will be made to circulate in separate pipes and will then be made to collide at a centre-of-mass energy of 14 TeV. The total energy stored in each beam will be 362 MJ, which is sufficient to melt 500 kg of copper. Safety of operation in the presence of such extremely powerful beams is a very important issue. To assess the damage caused by an accident that involves loss of an entire beam, we carried out numerical simulations of the impact of one of the LHC beams on a cylindrical solid copper target. These simulations, that have been published in [26], showed that if one uses a dynamic model, the proton beam will penetrate up to about 30 m in solid copper. However, a very interesting outcome of this study was that an LHC beam can be a very efficient tool to induce high-energy-density (HED) states in matter. The purpose of this paper is to summarize the relevant outcome of this work published in [27] for this conference, since it might be an additional, interesting application of the LHC.

The energy deposited by the 7 TeV proton beam in solid copper has been calculated using the FLUKA code [28] which is a well-established particle interaction and transport Monte Carlo code capable of simulating all components of the particle cascades generated by high-energy protons in matter up to TeV energies. The target is considered to be a cylinder of solid copper and the beam is incident on one face of the cylinder. The energy deposition problem is three dimensional, while the BIG-2 code [16] used to simulate the hydrodynamic and thermodynamic response of the target is two dimensional. We therefore consider the longitudinal position $L = 16$ cm where the maximum energy deposition occurs and study target dynamics along the cross section.

Figure 4 shows the material physical state at $t = 2000$ ns, which is the time when only 80 out of 2028 bunches have been delivered. It is seen that the material within 1 mm radius at the centre has been converted into a plasma which is followed by a hot liquid zone that extends up to 8 mm. A melting front is also seen moving outwards into the solid part of the target.

4. Diagnosing plasma at the core of the Sun

All stars including our neighbouring Sun provide a deep insight into the physics of fusion as well as the physics of HED matter including hot dense plasmas. Study of the interior of the Sun will therefore provide information that will be very useful to the above fields. One of the methods to achieve this goal is detection of hypothetical dark matter [29] particles known as axions. Inside the core of the Sun, axions could be produced by coherent conversion of thermal

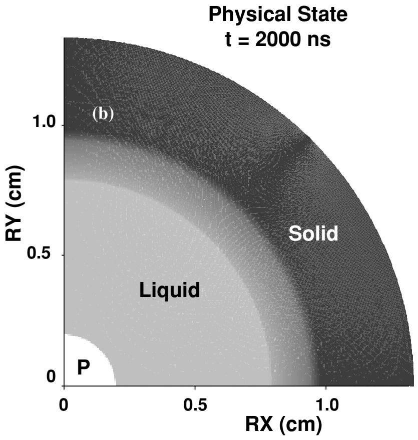

Figure 4. Material physical state (cross-sectional view, RX and RY represent radial coordinates) of a copper cylindrical target irradiated by the LHC beam at $t = 2000$ ns (only 80 out of 2028 proton bunches have been delivered by this time).

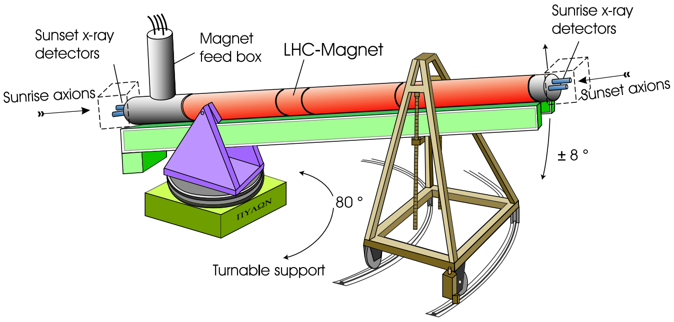

Figure 5. Experimental setup of the CERN Solar Axion Telescope (CAST).
(This figure is in colour only in the electronic version)

photons interacting with the electromagnetic field of charged particles of solar plasma (the Primakoff effect). At CERN, an experiment known as CAST (CERN Solar Axion Telescope) has been organized [30] for the detection of axions by converting them back into x-ray photons inside a strong transversal magnetic field (the experimental setup is shown in figure 5). The conversion probability of axions into photons is proportional to the square of the strength of the magnetic field. A strong magnetic field is thus essential to achieve a high sensitivity of the experiment. The experimental setup of CAST is shown in figure 5.

The heart of CAST is a prototype LHC superconducting magnet providing a dipole magnetic field of about 9 T in the interior of two parallel pipes over a distance of 9.26 m. On both sides of the magnet, x-ray detectors are looking for a potential axion signal as an excess signal over detector background. A TPC detector covers two magnet bores on one end looking for axions during sunset and an x-ray telescope with a pn-CCd detector is looking for axions at sunrise. The magnet can be pointed towards the Sun for about 1.5 h during sunrise and sunset, resulting in 3 h observation time per day. The remaining time is used for systematic background studies. The most sensitive detector system of CAST is the Wolter I type x-ray telescope which enhances the signal-to-background ratio by about a factor of 100 by concentrating the potential signal flux on a small spot on the pn-CCD detector. During the last 2 years, CAST has taken data for about 12 months, 6 months during 2003 and 2004 each. Analysis of the data collected in 2003 shows no excess signal over background and allows us to set a new limit on the axion-to-photon coupling $g_{a\gamma\gamma} \leqslant 1.6 \times 10^{-10}$ GeV^{-1}. Thus, CAST is the first experiment coming close to the astrophysical limit for the axion–photon coupling derived for the coupling constant from global clusters. The analysis of the 2004 data is still in progress.

5. Conclusions

Numerical simulations have shown that the intense uranium beam that will be generated at the future FAIR facility will be a very useful tool to study states of HED in matter. Two very different schemes, namely HIHEX and LAPLAS, can be employed to carry out such studies. The former scheme involves isochoric uniform heating and subsequent isentropic expansion of the heated material that will allow one to access very interesting physical states of HED matter that are either very difficult to access or even inaccessible using the traditional methods of shock compression. The latter scheme, on the other hand, allows one to achieve a low-entropy compression of a sample material such as hydrogen or water that is enclosed in a cylindrical shell of a high-*Z* material such as Au or lead. It has been found that such an implosion would generate physical conditions that are expected to exist in the interiors of giant planets. In addition, we carried out simulations to assess the damage caused by the full impact of an LHC beam on the equipment. We considered a solid copper target and a 'spin-off' of this study was that such an impact will generate HED states in matter. We also summarize results of an experiment that has been performed at CERN to detect exotic particles called axions. This experiment also provides means to diagnose the HED matter that exists in the interior of the Sun.

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