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Quasi-isochoric ion beam heating using dynamic confinement in spherical geometry for X-ray scattering experiments in WDM regime

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Abstract

Extreme states of matter such as Warm Dense Matter "WDM" and Dense Strongly Coupled Plasmas "DSCP" play a key role in many high energy density experiments, however, creating WDM and DSCP in a manner that can be quantified is not readily feasible. In this paper, isochoric heating of matter by intense heavy ion beams in spherical symmetry is investigated for WDM and DSCP research: the heating times are long (100 ns), the samples are macroscopically large (millimeter-size) and the symmetry is advantageous for diagnostic purposes. A dynamic confinement scheme in spherical symmetry is proposed which allows even ion beam heating times that are long on the hydrodynamic time scale of the target response. A particular selection of low-Z target tamper and X-ray probe radiation parameters allows to identify the X-ray scattering from the target material and use it for independent charge state measurements Z^* of the material under study.

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1. Introduction

The part of the phase diagram related to near-solid density and temperatures comparable to or greater than the Fermi energy is called "Warm Dense Matter" (WDM) [1]. It is a regime of strongly coupled plasmas, where correlation effects influence the behaviour of atoms and ions. The theoretical description of strongly coupled plasmas is difficult, as the perturbative approach used in standard plasma theory cannot be applied. Density effects, like pressure ionization, are important in the WDM regime and can influence the internal structure of ions and atoms. WDM studies are relevant for planetary science, cold star physics and indirect driven ICF. In the laboratory the WDM states occur in all plasma devices that start from solid matter: laser- and particle-beam driven plasmas, exploding wires, Z- and X-pinches.

Although these extreme states play a key role in many high energy density experiments, creating WDM and DSCP in a manner that can be quantified is not readily feasible. The possibility to obtain experimental data on radiative properties and the equation-of-state of WDM is restricted by the lack of drivers that can provide well-characterized heating of an isolated sample. The development of new methods to create and interpret the radiative emission of WDM/DSCP is therefore urgently required.

The creation of WDM/DSCP by means of intense heavy ion beams is a promising way for this research. Heavy ions can be accelerated to high energies, so that they can penetrate deep

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into matter and deposit their energy quite homogeneously given that the Bragg peak remains outside the sample. The laser-produced proton beams have very short pulse duration, but the particle energies are not high enough to heat an extended volume of condensed matter [2,3]. The energy deposition of heavy ions in matter is known with good accuracy until the temperature gets so high that plasma effects have to be taken into account [4]. Isochoric heating with heavy ion beams has the advantage that the internal energy of the sample can be calculated from the known ion beam parameters and the target contains no sharp gradients. Isochoric heating limits the pulse length of the ion beam according to the hydrodynamic response for the deposited energy and ion beam focal spot size.

The world-wide great interest in the research of WDM created by intense heavy ion beams has led to the formation of the ''WDM-collaboration'' where currently more than 20 laboratories from the US, Japan, France, Germany, the UK, and Russia are involved [5,6]. The WDM-collaboration has successfully submitted a technical design proposal [7] to employ intense heavy ion beams at GSI/FAIR [8] to create WDM-samples and to perform atomic and radiation physics studies by means of an independent X-ray scattering diagnostic driven by the PHELIX-laser at GSI [9], a technique that has been under development as a WDM diagnostic over the past decade [10–15].

The existing SIS-18 accelerator at GSI is currently being upgraded and will deliver up to 2×10^{11} ions of U^{28+} in the year 2009 [16]. This number of ions will be sufficient to heat solid hydrogen to a temperature of about 1 eV so that WDM experiments have also been proposed with the SIS-18 ion beam [5,6]. The ion beam pulse, however, will have a length of 100 ns (full width), which causes hydrodynamic expansion during the heating pulse, so that the conditions of isochoric heating are not fulfilled. A novel target design called ''dynamic confinement'' was proposed by the authors to control the hydrodynamic response of matter heated with the SIS-18 ion beam and maintain a cylindrical sample of constant density [17]. In dynamically confined targets the conditions of quasi-isochoric heating are provided by employing a thin low-*Z* tamper heated by the wings of the ion beam to produce confining pressure on the core target material. The use of a high-*Z* tamper is excluded by the envisaged scattering diagnostics with the few kiloelectron volt X-rays produced with the help of the PHELIX-laser. It was demonstrated that the dynamic confinement scheme in cylindrical geometry can be optimized to minimize the density variation during the heating phase or, alternatively, to obtain a mean density equal to the initial density after irradiation.

The present work extends the dynamic confinement scheme to spherical target geometry. Using spherical geometry provides better temperature homogeneity in the target core, larger mass of confined material, and lower linear density of the tamper after irradiation. The tamper thickness can be changed to modify the behaviour of the mean core density as in the cylindrical case. The spherical target can be used for a wider range of ion energies. To show the advantages of the spherical configuration for the scattering diagnostics, the hydrodynamic calculations were performed using the same ion beam parameters and target materials as for the cylindrical target.

The paper is structured as follows. Section 2 of this paper presents the hydrodynamic calculations of the dynamically confined target in spherical geometry and a comparison with the cylindrical case. In Section 3 particular issues of the X-ray scattering from dynamically confined targets are discussed. The conclusions are given in Section 4.

2. Spherical target with dynamic confinement scheme

The work on dynamic confinement was forced by the need for an ion beam target which can provide isochoric heating of solid matter with the SIS-18 ion beam and is accessible for X-ray scattering diagnostics. For the interpretation of the scattering data it is important to have homogeneous density and temperature distributions in the heated sample. The time resolution of the diagnostics is determined by the duration of the X-ray burst, which is short on the hydrodynamic time scale of the ion beam heated target.

The presented calculations were carried out with the help of the two-dimensional CAVEAT code [18]. The code uses a conservative finite-volume numerical technique in which all state variables are cell centred. Spatial differencing is performed assuming the linear variation of variables across the cell (second order scheme). The transport of material between the cells is allowed to support mesh motion according to the Arbitrary Lagrangian–Eulerian (ALE) technique. The code is able to handle tabular equations of state from the SESAME library [19]. The ion beam energy deposition is modelled by ray-tracing. In the presented dynamic confinement target temperatures of about 1 eV are achieved, therefore the stopping power data from the SRIM code [20] for cold materials are used. Using the Bloch stopping formula, the Coulomb logarithm for cold matter and fully ionized solid density plasma can be calculated for 200 MeV/u uranium ions. For hydrogen the calculation results in $(L^{\mathrm{plasma}} - L^{\mathrm{cold}})/L^{\mathrm{plasma}} \cong 0.09$. For the partially ionized WDM regime the error in the stopping power will be even smaller. Due to the practically homogeneous energy loss of the energetic heavy ion in low-*Z* targets of a few hundred micrometer thickness, a constant heating rate along the beam direction was assumed.

An ion beam consisting of 8×10^{10} uranium ions was considered for the calculations. This is well below the SIS-18 incoherent space charge limit of 2×10^{11} ions for U^{28+}, and will be available for experiments from 2009. The ions accelerated to 200 MeV/u will be delivered in 100 ns pulses (full width). The temporal beam shape is approximated by a parabola. Using a system of quadrupole magnets, the beam can be focused down to 350 μm standard deviation of a Gaussian distribution (FWHM = 815 μm).

For the first experiments solid hydrogen was chosen as the core target material. The high sublimation energy of carbon makes it a natural choice as a low-*Z* tamper material. The calculations have shown that the tamper should have a density below the density range of pure carbon. Therefore, carbon phenolic made of 70% carbon and 30% phenolic resin having