Dynamic confinement of targets heated quasi-isochorically with heavy ion beams

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Isochoric heating of matter by intense heavy ion beams promises to become a fruitful approach to warm dense matter studies. For heating times that are long on the hydrodynamic time scale of the target response a tamped target is essential. The proposed dynamic confinement provides homogeneous target heating by a low-Z tamper, which allows one to apply powerful x-ray scattering diagnostics. To demonstrate the potential of the method, heating of a hydrogen sample with the SIS-18 beam at GSI Darmstadt is investigated numerically. The intense x-ray bursts for diagnostics can be provided by the PHELIX laser currently installed at GSI. In the optimized heating regime, density variations can be reduced to a level of 15% from the initial density value.

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I. INTRODUCTION

Intense beams of energetic heavy ions have the advantageous property to deposit their energy with good uniformity over an extended volume. For ion energies $E_i \gtrsim 100$ MeV/u, the stopping power of most materials is known to an accuracy of a few percent and is insensitive to details of chemical structure of the stopping material. Hence, with a given beam current density profile, the total deposited specific energy ϵ is known to an accuracy of a few percent. When the density of the heated sample, ρ_0, remains unchanged, the thermodynamic state of matter after irradiation is completely defined by the two quantities ϵ and ρ_0. In this case any measured physical quantity is determined as a function of this well defined thermodynamic state.

The SIS-18 synchrotron at GSI Darmstadt is able to provide intense beams of energetic heavy ions. Up to 2×10^{11} ions of U^{28+} accelerated to 200 MeV/u will be available in the near future [1]. When focused on a spot with a radius of $\lesssim 0.5$ mm (standard deviation of the Gaussian distribution), this ion beam will provide—in hydrogen, for example—an energy deposition of $\epsilon \gtrsim 100$ kJ/g (1 eV/atom). Hydrodynamic consistency between the deposited energy and the focal spot radius sets a limit on the pulse duration for the ion beam.

Hydrodynamic expansion of heated sample, which should be minimized for quasi-isochoric experiments, is sensitive to the spatial profile of the ion beam current. For a rectangular radial profile, the density in the target center begins to drop only after a time $t_s = r_b/c_s$ (r_b is the focal spot radius, and c_s is the sound speed), when the rarefaction wave reaches the axis of the target. More realistic would, however, be a Gaussian current density profile. In this case, when the second spatial derivative of pressure is not zero, the density begins to drop in the vicinity of the target axis from the very start of the ion pulse. A typical example of this type of hydrodynamic motion which can be solved analytically is an isentropic expansion of a sphere with a parabolic pressure profile [2]. To keep the target density sufficiently constant during irradiation by a beam with the above parameters, a pulse duration below 20 ns is needed. According to the current plans, SIS-18 will deliver beam bunches not shorter then 100 ns. The dynamic confinement of irradiated samples investigated below is aimed at suppressing the hydrodynamic motion during heating by long beam pulses and maintaining a constant density sample.

The choice of materials for our target is dictated primarily by the proposed method of diagnostics, which is based on measuring the intensity, spectral and angular distributions of x rays (in several keV range) scattered by the heated sample. Being able to provide valuable information on ion-ion correlations, electron and ion temperatures [3,4], the x ray-diagnostics has a potential to become a powerful tool in investigating the properties of warm dense matter [5]. At GSI, the required pulsed x-ray source can be powered by the kilojoule PHELIX laser [6] (providing a nanosecond time resolution). However, with probe x rays in the keV range, we are restricted to targets consisting of low-Z elements. For diagnostic purposes it is very advantageous to have a homogeneous density distribution in the target volume to interpret the scattering data. To illustrate the method of dynamic confinement, solid hydrogen was chosen as the principal target material. High-density hydrogen will also permit one to perform interesting atomic physics studies of the self-emission.

Section II of this paper describes parameters of the ion beam provided by the SIS-18 synchrotron at GSI. In Sec. III, possibilities to confine the heated material by increasing the number of ions are discussed, and a target design for dynamic confinement of a hydrogen sample heated by heavy ions is proposed. Capabilities of x-ray diagnostics of ion beam driven targets powered by the PHELIX laser are discussed in Sec. IV.

II. GSI ION BEAM PARAMETERS

The heavy ion synchrotron SIS-18 at GSI Darmstadt is able to deliver intense beams of energetic heavy ions suitable for creation of extended volumes of matter with high energy density. Currently the SIS-18 can provide about 10^{10} ura-

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nium ions with an energy of a few hundreds MeV/u. According to the accelerator parameters, the incoherent space charge limit allows acceleration of up to 2×10^{11} ions of U^{28+} to an energy 200 MeV/u, while several times 10^{10} particles can be reliably expected on target [1]. Introduction of a powerful rf buncher leads to a pulse compression that will provide pulses with a length of the order of 100 ns. To perform numerical calculations, we used a triangular temporal pulse power profile, which is close enough to the real beam shape. The spatial profile of the ion beam current is well approximated by a Gaussian distribution, $j\sim\exp(-r^2/2r_{\rm b}^2)$, where $r_{\rm b}$ is the focal spot radius. By employment of a quadrupole focusing system, the ion beams can be focused down to a spot radius of less than 0.5 mm. The beam energy of 200 MeV/u was chosen because it corresponds to the maximum magnetic rigidity of 18 Tm, which can be handled in the synchrotron. Lower energies are not desirable due to a reduced efficiency of the rf buncher.

The governing parameter for proposed beam matter interaction experiments is the specific energy deposition. Solid hydrogen heated quasi-isochorically to a temperature of about 1 eV would correspond to a regime of warm dense matter, which is interesting for investigation [5]. For our analysis a specific energy of 130 kJ/g deposited in the center of the Gaussian beam distribution in a hydrogen sample was chosen. According to the SESAME equation of state, this corresponds to a temperature of about 0.6 eV in solid hydrogen, if the beam energy is fully converted into the internal energy. A corresponding ion beam from SIS-18 would consist of 8×10^{10} uranium ions with an energy of 200 MeV/u focused on $r_{\rm b}=350$ μm.

III. TARGET SIMULATION RESULTS

Numerical simulations of the target hydrodynamics have been carried out with the two-dimensional hydrodynamics code BIG-2 [7] supplemented by the SESAME equation of state tables [8]. The energy deposition of heavy ions was calculated using the SRIM code [9]. The results are shown for a bare as well as a tamped cylindrical hydrogen sample. According to the simulations, the SIS-18 is not able to deliver a sufficient number of ions to heat a bare sample quasi-isochorically, therefore a target configuration with a tamper has to be used. A schematic view of the tamped sample is shown in Fig. 1.

A beneficial property of energetic heavy ions to heat matter nearly uniformly along the initial part of their trajectory ensures quasi-isochoric conditions along the beam axis, if the target is long enough, and expansion waves from the ends do not disturb the probed volume. It allows one to reduce the target hydrodynamics to a one-dimensional problem, i.e., to perform the simulations only along the radius.

A. Bare hydrogen sample

The simplest target for quasi-isochoric experiments would be a bare sample of hydrogen, with a radius $R_{\rm H}\gtrsim r_{\rm b}$, if the density would stay constant at least in part of the sample. For a rectangular spatial profile of the beam current, the density

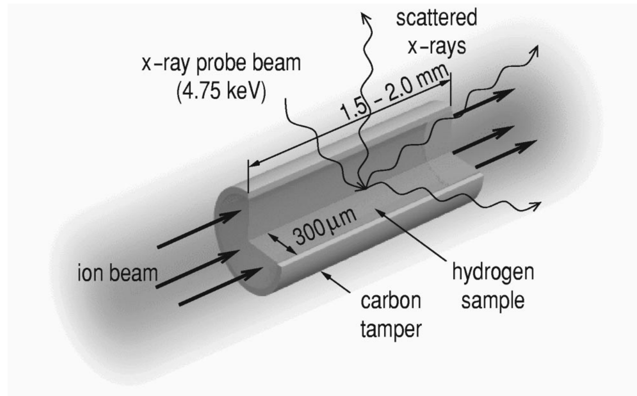

FIG. 1. Target configuration for dynamic confinement of frozen hydrogen heated by the ion beam available from the SIS-18, and possible x-ray diagnostics.

in the center of the irradiated region remains constant until the rarefaction wave arrives. However, for a Gaussian profile with a nonzero second spatial derivative of the pressure profile on the target axis the density begins to drop long before the rarefaction wave reaches the target center.

Figure 2 shows the density and temperature evolution in the center of a sample made of frozen hydrogen, during and shortly after irradiation by a Gaussian ion beam. Two cases are shown: in the first case the ion beam consists of 8×10^{10} particles, while in the second case the number of ions is increased by a factor of ten, and the focal spot radius is increased by $\sqrt{10}$ to keep the energy deposition equal to 130 kJ/g.

For 8×10^{10} ions, which is a realistic beam intensity for SIS-18, the density at the axis drops by a factor of two during the irradiation time, and the goal of quasi-isochoric heating is not reached. However, still interesting self-emission studies of high density hydrogen can be performed (e.g., optically thin emission of the Balmer series). For the larger focal spot in the second case, which requires a higher number of ions, the density remains constant to a few percent, the temperature comes close to the maximum value of 0.64 eV. Hence, to heat a bare sample of matter quasi-isochorically by

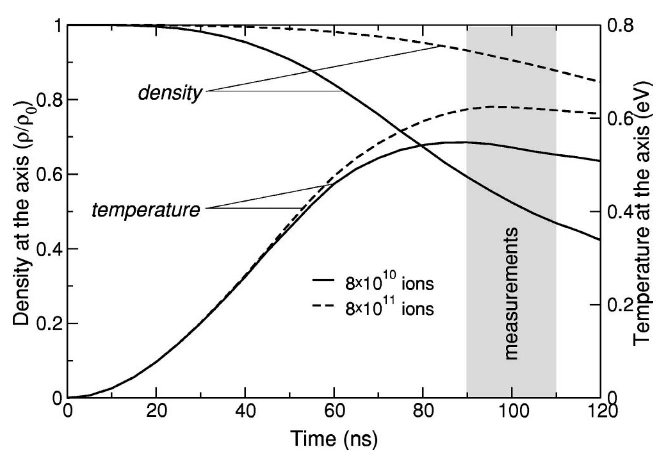

FIG. 2. Evolution of density and temperature on the axis of a bare sample for 8×10^{10} and 8×10^{11} ions per pulse. The ion pulse length is 100 ns.

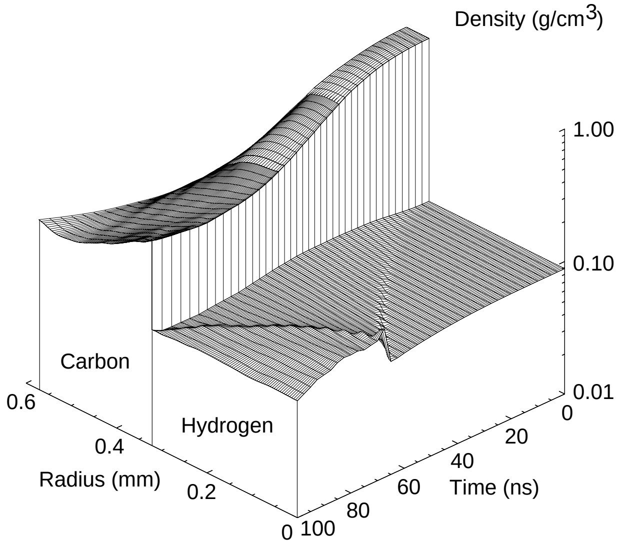

FIG. 3. Density distribution vs radius and time for the target shown in Fig. 1 during the ion beam irradiation.

the SIS-18 ion beam, an intensity exceeding the incoherent space charge limit of the machine would be required.

B. Tamped sample (dynamic confinement)

With a limited number of ions, the adverse effects of the hydrodynamic expansion can be reduced by introducing an appropriate tamper adjacent to the hydrogen. The use of a massive, heavy-metal tamper is excluded by the need for a target to be transparent to keV x rays. To achieve confinement with a low-Z material, the tamper has to be heated by the wings of the ion beam in order to produce confining pressure on the main target material.

Also, it is beneficial to use tamper material with a large sublimation energy to delay the beginning of the hydrodynamic motion of the tamper. A carbon tamper would be a natural choice. First simulations have shown, however, that the tamper density should lie below the normal density of graphite. As an appropriate substitute, the so called carbon phenolic was chosen. Carbon phenolic is a composite which is widely used in aerospace technology as a protective ablative material, made of about 70% carbon cloth which is bound by 30% of phenolic resin. According to the SESAME equation of state, it has a density of 1.5 g/cm^3 at normal conditions. The radius of the hydrogen core R_H and the thickness of the carbon tamper ΔR_C (see Fig. 1) were optimized in numerical simulations. The smallest variations of the density of hydrogen were found for $R_H = 300\,\mu$m, $\Delta R_C = 50\ \mu$m.

The overall target behavior is shown in Fig. 3. During the ion pulse the carbon tamper expands outward from its initial thickness of 50 μm to a thickness of 220 μm, and its density drops to about 0.3 g/cm^3. At the same time, the interface between the tamper and the hydrogen core moves only slightly, and the density of hydrogen remains almost constant except for a weak shock wave that is launched by the tamper at the beginning of the beam pulse. This shock wave is reflected from the target axis and arrives back at the tamper by the end of the ion pulse.

The quasi-isochoric heating of hydrogen is ensured by two competing processes: expansion of the hydrogen core and expansion of the carbon tamper. Initially, the hydrogen density begins to decrease on the target axis due to the Gaussian heating profile. At the same time, the pressure in the carbon tamper is higher than the pressure in the hydrogen core, and the C/H interface moves inward. Later on, as the density in the tamper drops, the pressure in the tamper decreases and the motion of the boundary comes to a halt. At still later times the increasing pressure in the core pushes the C/H interface back into its initial position.

Figure 4 shows the radial density and temperature profiles in hydrogen at different times. The solid lines relate to the target configuration shown in Fig. 1, while the dashed lines assume the ideal isochoric heating of frozen hydrogen by the same ion beam. At $t = 60$ ns the density near the axis is de-

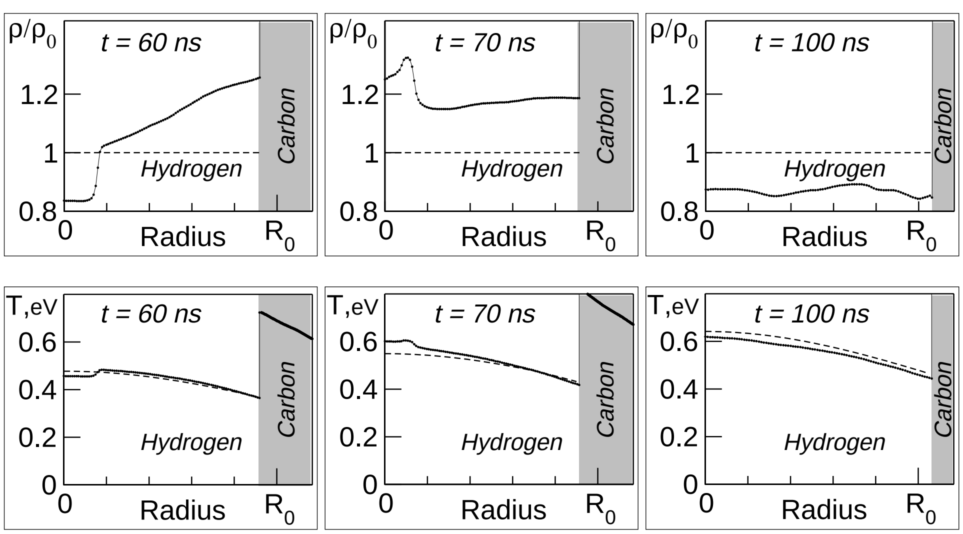

FIG. 4. Radial density and temperature profiles in tamped solid hydrogen. The heavy ion beam consists of 8×10^{10} ions of U^{28+}. Solid lines correspond to a confined sample and dashed lines illustrate the ideal isochoric heating.

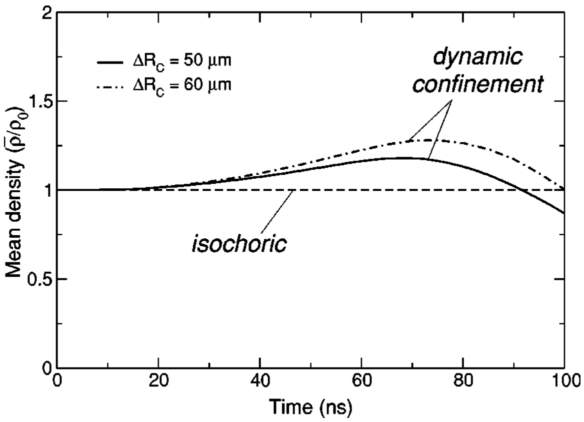

FIG. 5. Evolution of the mean hydrogen density during the ion beam heating for two different thicknesses of the tamper.

pressed, and the tamper moves inward and launches a weak shock wave. At $t=70$ ns motion of the interface stalls, hydrogen is compressed by about 18%, and the reflected shock wave is running outward. At the end of the beam pulse, the density distribution along the radius is practically uniform, and differs by about 15% from the initial density of the frozen hydrogen. The temperature is $\sim 4\%$ less than that in the case of the ideal isochoric heating.

In Fig. 5, the time evolution of the mean hydrogen density, averaged over the radius, is shown. The solid line corresponds to the thickness of the tamper of 50 μm. In this configuration the smallest variations of the mean density during the beam heating were found. The dashed-dotted line is calculated for a 60-μm-thick tamper. In this case the density of hydrogen after irradiation is equal to its initial value.

Note that the performed one-dimensional simulations also provide the necessary information required to estimate the target length. It is seen that sound propagates twice the radius of hydrogen (300 μm) during the ion pulse. Hence, depending on the diagnostics requirements, the target has to be 1.5–2.0 mm long. Since the range of 200 MeV/u U ions in solid hydrogen is 45 mm, in carbon phenolic it is 6.4 mm, a good uniformity along the beam axis can be guaranteed.

IV. PROPOSED DIAGNOSTICS

Warm dense matter (WDM) is the region in temperature (T) and density (ρ) which is not described as normal condensed matter, i.e., $T\approx 0$, and not described by theories of weakly coupled plasmas. The relevance of WDM studies arises from the wide occurrence of this region between solids and plasmas. It can be found in the interior of planets, cool dense stars, and all plasma production devices, which start from cold dense matter (e.g., z and x pinches, laser solid matter interaction, heavy ion beam driven plasmas, capillaries, exploding wires). With increasing plasma coupling parameter (which is the ratio of the interatomic potential energy to the thermal energy), perturbation approaches used in standard plasma phase theories fail because of the lack of small expansion parameters. To develop new theoretical methods, which could describe strongly coupled plasmas as well as high temperature condensed matter, we must be able to probe these matter states experimentally. Isochoric heating of a macroscopic sample in the WDM regime opens a way to isolate such WDM states and allows conclusions on the mean ion charge from measurements of the electron density.

A. X-ray scattering diagnostic

For hydrogen, the warm dense matter parameter region is roughly $\rho=10^{-3}$–1 g/cm^3, $T=0.1-20$ eV [5]. At high densities and relatively low temperatures, self-emission in the x-ray range is generally rather weak. If the level of this radiation is too low to be observed experimentally, we have to probe the sample with external x-rays. Due to the small scattering cross sections, high intensity x-ray sources are required. Such backlighter sources can be realized with the kilojoule PHELIX-laser beam at GSI [6], e.g., using the thermally induced Heα x-ray emission of a mid-Z target element [e.g., Ti ($E=4.85$ keV), Fe ($E=6.6$ keV)] irradiated with nanosecond pulses or the hot electron induced hard x-ray Kα emission generated with very short laser pulses (1 ps, several 100 J).

X-ray scattering diagnostics can be used in two different modes. Spectrally unresolved scattering provides information about the ion correlation by scanning the scattering angle. A spectrally resolved diagnostics, using the nearly backscattering geometry, will allow the direct measurement of the ionization state, density, and temperature of the probed sample. Two aspects for the interpretation of the scattering data are important: the probe x rays should undergo only small absorption in the sample, and the radial density profile should be rather homogeneous to provide scattering from the same density. As it is shown in Fig. 3, the radial density distribution is quite homogeneous after about 100 ns of heating and, therefore, well suited. Moreover, the low-Z tamper does not lead to strong absorption of the probe beam. Both collective and noncollective spectrally resolved scattering regimes are accessible in dependence on scattering angles or by tuning the x-ray energy using different backlighter target elements. With that, a wide range of scattering data can be provided for the investigation of strongly coupled plasmas [10].

B. Self-emission

Near a 1 eV temperature, hydrogen shows strong optical self-emission. Therefore, interesting atomic physics studies at high densities can be performed, e.g., electric field effects, line shifts and broadening, level depression. At number densities greater than 10^{18} cm^{-3}, an extremely interesting regime for Stark-broadening studies opens up. Estimates show that the Balmer series could be suitable emission lines for the analysis.

V. CONCLUSION

Isochoric experiments in the interesting parameter region (for warm dense matter studies at $T\gtrsim 0.5$ eV and a near solid density) with bare low-Z samples require beam parameters beyond the capabilities of the SIS-18 accelerator at GSI. As a consequence of hydrodynamic expansion, the density drops by about a factor of two during the beam irradiation. Introduction of a low-Z tamper, which is transparent for diagnostics x rays, improves the situation significantly: the density varies by 15–18 % from its initial value, the temperature is 4% less than that in the ideal isochoric case. This provides excellent conditions for x-ray scattering diagnostics setup with the kilojoule PHELIX-laser beam at GSI.

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