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Outline of experimental schemes for measurements of thermophysical and transport properties in warm dense matter at GSI and FAIR

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Abstract. Different experimental schemes for investigation of warm dense matter produced with intense energetic ion beams are presented. The described target configurations allow direct measurements of thermophysical and transport properties of warm dense matter without hydrodynamic recalculations. The presented experiments will be realized at the current GSI synchrotron SIS-18 and the future FAIR facility in the framework of the WDM-collaboration.

1. Introduction

Intense energetic ion beams are a promising tool for production and investigation of matter at high energy density. Using a beam from the SIS-18 heavy ion synchrotron at GSI a specific energy of several kJ/g can be deposited in an extended volume of condensed matter. Extreme states of matter at nearly solid densities and thermal energies comparable to the Fermi energy are referred to as warm dense matter (WDM). Understanding of WDM is difficult because of the complexity of first principle theories and the lack of well-defined experimental measurements [1]. For precise thermophysical experiments using heavy ion beams appropriate target schemes are indispensable.

In this paper we address three experimental schemes for investigation of WDM with intense ion beams. These schemes constitute currently the central experimental activities of the WDM-collaboration which is part of the core program of the international FAIR facility [2].

2. Experimental schemes

2.1. Isochoric heating

In the case of isochoric heating the density of a substance, ρ_0 remains constant and the energy deposited by the ion beam is equal to the internal energy of the heated matter, ϵ . Then any measured quantity is a function of a well defined thermodynamic state (ρ_0, ϵ) . The available ion pulses are not short enough, however, and the conditions for isochoric heating are not satisfied. Therefore, a dynamic confinement scheme was developed to realize isochoric heating of matter in cylindrical [3] as well as in spherical geometry [4]. Dynamically confined targets provide the conditions of quasi-isochoric heating by employing a thin low-Z tamper which is as well heated by the ion beam to produce a confining pressure on the core target material. The use of a low-Z tamper allows to apply X-ray scattering diagnostics to investigate the core target material [4].

An ion-beam target configuration in spherical geometry is drawn Fig. 1(a). Fig. 1(b) shows the normalized mean density variation in a target consisting of a hydrogen core surrounded by a carbon shell. It is seen that the target can be optimized to minimize the density variation during the heating phase or to obtain a mean density after irradiation equal to the initial one. In the calculation the hydrogen core has a radius of $400 \mu\text{m}$. The ion beam has 100 ns length and consists of 8×10^{10} uranium ions.

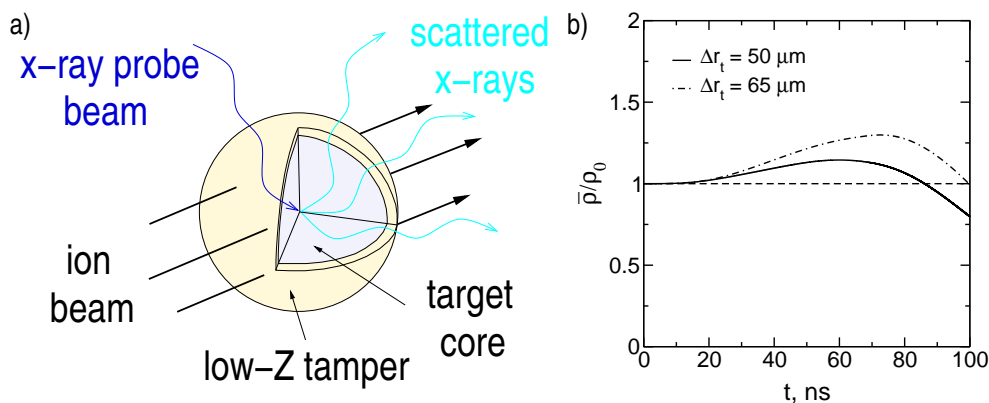


Figure 1. a) Dynamically confined target in spherical geometry. b) Mean density variation during the ion beam heating for two different tamper thicknesses.

2.2. Isothermal expansion

Heating of thin foils with intense heavy-ion beams allows the creation of isolated samples of warm dense matter suitable for experimental determination of frequency-dependent opacities [5]. The proposed measurements will help to benchmark atomic physics models in the WDM regime. For the material temperatures of about 1 eV the measurements have to be performed in the XUV-range. In the experiments at the GSI facility, a backlighter source is driven by a table-top laser as shown in Fig. 2(a). The higher ion beam intensities available at FAIR will allow to use a second ion-beam heated foil as a backlighter.

For precise opacity measurements a constant target temperature is essential. Figure 2(b) shows the density and temperature distribution in the initially 200 nm thick Bi foil irradiated with an ion beam. For the calculation an ion beam consisting of 10^{10} uranium ions with a pulse length of 100 ns is assumed. After 45 ns the target foil is expanded resulting in a gaussian density profile and a constant temperature of about 1 eV, which is appropriate for opacity measurements. Simulation results agree with an analytical treatment of the isothermal expansion of the heated foils given in [6].

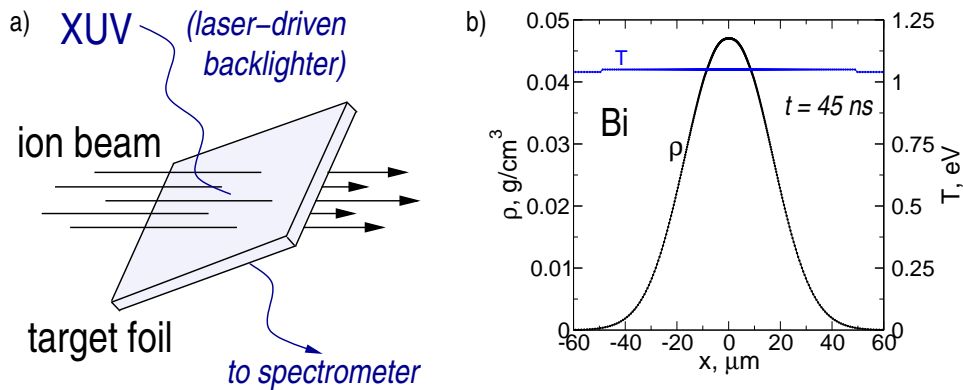


Figure 2. a) Ion-beam target and backlighter configuration for opacity measurements. b) Target density and temperature in the ion beam heated Bi foil.

2.3. Quasi-static heating

It was suggested to measure equation of state data using ion beam heating of foams which are highly dispersed porous samples. The main goal is to detect the moment t_x when the pores of the heated sample close [7,8]. At the moment t_x the density is determined by the mean density of the cold sample and the enthalpy, H by the ion beam energy deposition. Hence, the caloric expansion coefficient $\alpha_p = (\partial\rho/\partial H)_p$ is obtained. Since at $t = t_x$ the heated sample is fairly homogeneous, a measurement of the surface temperature defines the thermal expansion coefficient $\alpha'_p = (\partial\rho/\partial T)_p$ and the heat capacity $c_p = (\partial H/\partial T)_p$. The proposed experimental scenario can be applied, e.g. to a number of high boiling temperature metals in the temperature range of 1000–7000 K and will help to determine their critical points, which are highly uncertain for those metals [7]. Measurements with certain compounds can also confirm or disprove predicted non-congruent evaporation [7-9].

It is proposed to replace the complicated three-dimensional structure of a foam sample by a stack target consisting of n separated thin foils [10] as shown in Fig. 3(a). The gap between the foils determines the mean density of the target, $\rho_{00} = \rho_0 l_0 / (l_0 + \Delta l_0)$. Similar to foam samples, the porosity of the stack target can be defined as $\rho_{00}/\rho_0 < 1$. At $t < t_x$ the foils expand quasi-statically, if the sound propagation time is short on the time scale of the energy deposition. The later can be achieved if the foils are sufficiently thin. If the expansion is quasi-static, the density, the pressure, and the internal energy (and temperature) are constant in space. The surface velocity of the expanding foils is proportional to the foil thickness, $u_l \propto l$. When the foils merge, the launched acoustic waves increase the surface velocity of the entire target by $2u_l$, when escaping from the target surface.

The evolution of the surface velocity for a stack target consisting of $n = 10$ foils is presented in Fig. 3(b). For the hydrodynamic calculations a stack made of aluminum and an energy deposition of 10 kJ/g in a 100 ns pulse are assumed. This corresponds to about 10^9 ions of uranium. The initial foil thickness is $l_0 = 5 \mu\text{m}$, the gap between the foils is $\Delta l_0 = 1.1 \mu\text{m}$. The expected sharp increase of the surface velocity will help to detect the homogenization time t_x .

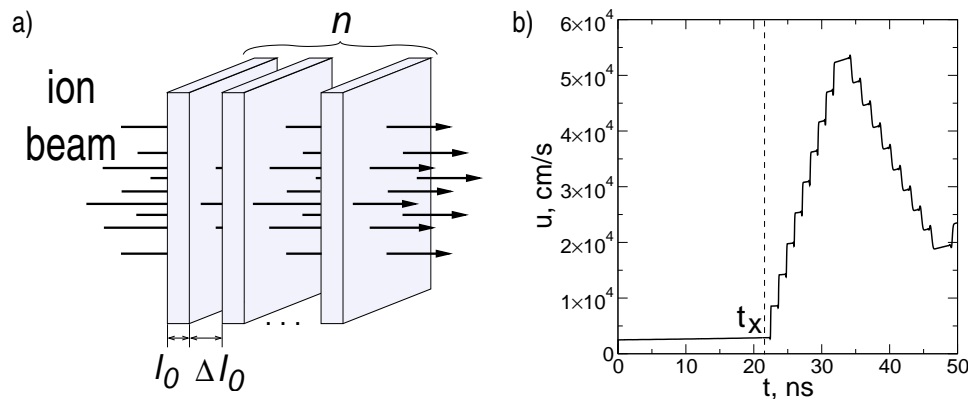


Figure 3. a) Stack target configuration. b) Surface velocity of a stack target consisting of 10 foils irradiated with an ion beam.

3. Summary

The described experimental schemes allow the determination of thermophysical and transport properties of WDM directly from experimental data without the necessity of intermediate hydrodynamic recalculations. The proposed schemes make use of isochoric heating, isothermal expansion and quasi-static heating of the irradiated samples. The presented experiments can be started using the existing heavy ion synchrotron SIS-18 at GSI. Use of the future FAIR facility will extend the accessible temperature range and improve the accuracy of the experiments due to the higher ion beam intensity.

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