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Quasi-static heating of stack targets with intense ion beams for equation of state measurements

An. Tauschwitz [a,b,*], V. Efremov [c], J.A. Maruhn [a], F.B. Rosmej [d,e], A. Tauschwitz [f]

[a] University of Frankfurt am Main, Max-von-Laue-Str.1, 60438 Frankfurt am Main, Germany
[b] ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[c] Joint Institute for High Temperatures, Moscow, Russia
[d] Université Pierre et Marie Curie, Paris, France
[e] Centre de Recherche LULI, Ecole Polytechnique, PAPD, Palaiseau, France
[f] Gesellschaft für Schwerionenforschung, Darmstadt, Germany

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ABSTRACT

A novel target configuration for equation of state measurements using intense ion beams is proposed. It is based on a stack consisting of several thin foils which expand quasi-statically when heated with the ion beam. The merging of the single foils causes a sharp increase of the expansion velocity. Together with the known energy deposition of the ion beam this allows direct determination of equation of state data. The parameters of the stack target were optimized with hydrodynamic calculations. Finally, a simple analytical model to predict the expansion velocity was developed.

1. Introduction

Intense energetic ion beams have become a promising tool for production and investigation of matter at high energy density. Using a beam from SIS-18 heavy ion synchrotron at GSI a specific energy of several kJ/g can be deposited in an extended volume of condensed matter. For precise thermophysical experiments using heavy ion beams appropriate target configurations have to be defined. One possible experimental scheme is based on isochoric heating of the investigated sample. In this case the density of the substance remains constant and the energy deposited by the ion beam, which is known with good accuracy, is equal to the internal energy of the heated matter. Hence, any measured quantity will be a function of a well defined thermodynamic state (ρ_0, e). The ion pulses available for the experiments are not short enough, however, and the conditions for isochoric heating of a bare sample are not satisfied. A special target configuration, the dynamic confinement scheme, was developed to realize isochoric heating of matter in cylindrical [1] as well as in spherical geometry [2] and to allow diagnostics with external X-rays [2]. Another type of experiment utilizes isothermal expansion of thin foils heated with a constant energy deposition per unit mass. If the foils are heated to temperatures of several eV, spectral opacities in the vacuum UV can be measured [3]. The constant temperature distribution in the heated foil is prerequisite for interpretation of the experimental data.

It was also suggested to measure equation of state data using ion beam heating of foams, highly dispersed porous samples. The main goal is to detect the moment t_x when the pores of the heated sample close [4,5]. This corresponds to the time when quasi-isobaric expansion of each single grain is terminated and quasi-isochoric heating of the bulk sample begins. An expected sharp increase of pressure can be used to register the time t_x. We cannot, however, think of a clear hydrodynamic response in the complicated three-dimensional structure of a foam sample. In this work we present a new target scheme, which is based on quasi-static heating of thin structures with heavy ion beams. To realize the proposed measurement we consider it essential to use a planar target

* Corresponding author. Address: University of Frankfurt am Main, Max-von-Laue-Str.1, 60438 Frankfurt am Main, Germany. Tel.: +49 6159 71 1327.
E-mail address: an.tauschwitz@gsi.de (An. Tauschwitz).

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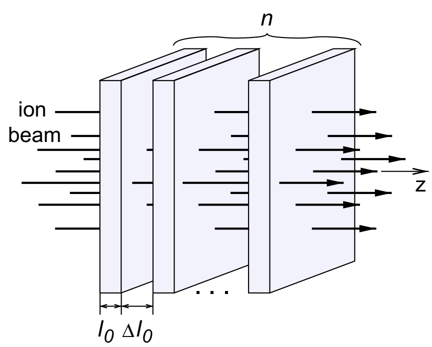

Fig. 1. Schematic view of the ion beam – stack target geometry.

geometry with a clear hydrodynamic response in one-dimensional. This can be implemented in form of a stack structure consisting of thin foils. The presented hydrodynamic calculations show that the parameters of the stack target can be optimized for precise measurements.

In Section 2 quasi-static heating of stack targets is described. In Section 3 hydrodynamic calculations and analytical analyses of the stack targets are presented.

2. Quasi-static heating of stack targets

Quasi-static expansion of condensed matter is a limiting case of hydrodynamic motion and means that the density change is small, $\Delta\rho/\rho \ll 1$ within the time of sound propagation through the sample. This condition can be satisfied if the target foils are sufficiently thin. If the expansion is quasi-static, the density, the pressure, and the internal energy (and temperature) are constant in space, while the velocity is a linear function of position at any time. The surface velocity of the expanding foils is proportional to the foil thickness. The kinetic energy is much smaller than the internal energy of the sample.

The geometry of an ion beam heated stack target is presented in Fig. 1. The stack target consists of n separated thin foils with thickness l_0. The direction of the ion beam is perpendicular to the foils. The gap between the foils, Δl_0 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 the time t_x, when the expanding foils merge, the thickness of the foils is $l = l_0 + \Delta l_0$. If the foil thickness is much smaller than the ion beam spot the expansion of the foils in the direction of the ion beam is planar and one-dimensional.

At the moment t_x the density is determined by the mean density of the cold sample and the enthalpy ($H = e + p/\rho$) 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 $c_p = (\partial H/\partial T)_p$ [4,5]. The proposed experimental scenario applied, e.g. to liquid uranium in the temperature range of 1000–7000 K will help to determine the critical point, which is highly uncertain for this metal. Measurements with uranium-containing compounds like uranium dioxide can confirm or disprove predicted different chemical compositions of coexisting phases, which is referred to non-congruent evaporation [4,6,7].

3. Hydrodynamic calculations

To predict the hydrodynamic response of liquid metals exposed to volumetric heating by the ion beam, we applied a two-term Mie-Grüneisen equation of state [8]

$$p = p(\rho, e) = p_c(\rho) + p_T(\rho, e) = p_c(\rho) + \Gamma\rho(e - e_c(\rho)), \tag{1}$$

where p, ρ, e are, respectively, the pressure, the density, and the specific internal energy, p_c and e_c denote the cold pressure and energy. The Grüneisen coefficient Γ characterizes the ratio of the thermal pressure p_T to the thermal energy $e_T = e - e_c$. For the cold pressure we used a second order Birch-Murnaghan isotherm

$$p_c(\rho) = \frac{3}{2}\rho_0 c_0^2 \left[\left(\frac{\rho}{\rho_0}\right)^{\frac{7}{3}} - \left(\frac{\rho}{\rho_0}\right)^{\frac{5}{3}}\right], \tag{2}$$

where c_0 is the sound speed at normal density $\rho = \rho_0$ and zero pressure. The cold pressure p_c is related to the potential energy by $\rho^2 de_c/d\rho = p_c$. Since the thermal pressure is always positive, $p_T > 0$, the cold pressure gets negative, $p_c < 0$, when the thin foil expands quasi-statically along $p \approx 0$. First calculations were done using the material constants for aluminum taken from [8], $\rho_0 = 2.7$ g/cm^3, $c_0 = 5.2 \cdot 10^5$ cm/s, $\Gamma = 2.1$. The simulations have been performed using the hydrodynamic code Caveat [9].

For the hydrodynamic calculations a stack made of aluminum and an energy deposition of 20 kJ/g in a single sine-squared 100 ns pulse are taken, which is realistic for the present SIS-18 facility. To model the expansion of the liquid metal, a mean density $\rho_{00} = 2$ g/cm^3 is assumed. To study the hydrodynamic response of the target, a stack structure made of $n = 10$ foils is considered. For the measurement the number of foils has to be chosen according to the accuracy requirements of the experiment.

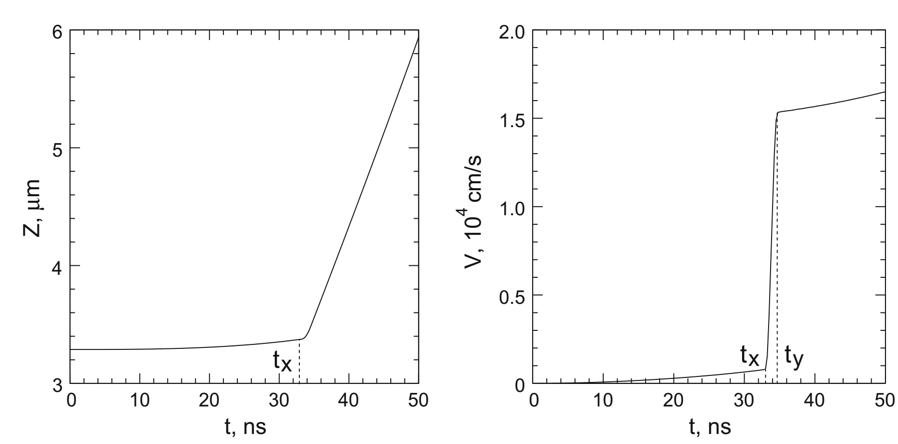

Fig. 2. Position of the stack surface, Z, and the surface velocity, V, as functions of time for the initial foil thickness $l_0 = 0.5$ μm and a gap of $\Delta l_0 = 0.175$ μm($\rho_{00} = 2$ g/cm^3).