Nuclear Instruments and Methods in Physics Research A 733 (2014) 4–7

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Numerical study of heavy-ion stopping in foam targets with one-dimensional subcell-scale hydrodynamic motions

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ARTICLE INFO

Available online 3 June 2013

Keywords:
Heavy-ion beam
Stopping power
Warm dense matter
Foam target
Hydrodynamics
Numerical simulation

ABSTRACT

Heavy-ion stopping in foam targets with subcell-scale hydro motions was numerically investigated in relation to ion-driven warm dense matter experiments. To simulate porous foam targets, we employed a simple 1D periodic multilayer model consisting of thin solid slabs and gaps between them. The averaged pore diameter and cell-wall thickness of the foam were represented by the gap width between the slabs and the slab thickness, respectively. The density- and temperature-dependent projectile stopping cross-sections were evaluated using a binary encounter model taking into account the electronic state of target atoms during heating and expansion. We employed a combination of $_{11}$Na projectiles and subrange $_{13}$Al foam targets with $\rho=0.05\rho_{solid}$. The hydrodynamic motion of the target was calculated with a 1D code. During homogenization, hot dense spots appeared at the original gap positions, owing to stagnation of the jets. As a result, even after the pores were filled with blow-off materials, the initial inhomogeneity was not completely smeared out, and the total energy loss was still not equal to that in the homogeneous equivalent, especially for large pore sizes.

1. Introduction

It is known that heavy-ion stopping is enhanced when the target is highly ionized [1–3]. Similar effects are observed not only for ionization but also for other changes of electronic state in the target. Stopping cross-section per target atom can change even by liquid–gas transitions. Valence electrons in gas-phase molecules are more weakly bound than those in condensed matter. Hence electrons in gas-phase targets can easily be excited or ionized, giving the projectile more chance of energy deposition. It follows that, generally, gas phase shows higher stopping cross-sections than condensed phase [4].

Low density foams are widely used as targets for inertial fusion experiments. By using foams, target density and size can be independently controlled in accordance with the purpose of the experiment. From a microscopic point of view, a foam is a complex heterogeneous mixture of solid and vacuum (or gas). Such a microstructure changes with hydrodynamic motion including melting and evaporation of solid phase during heating. The projectile stopping is due to the solid phase of the target when the irradiation starts. After the start of hydro motion of the small pore structure, a mixture of solid and its vapor with different temperature, density, ionization and excitation is responsible to the projectile energy loss. Thus, the change of the projectile stopping power in foams during heating can be very complex. However, in designing beam parameters of ion-driven warm dense matter (WDM) experiments with low-density foam targets [5], the foams are usually regarded as homogeneous media, and the stopping cross-section is assumed to be equal to that of homogeneous room-temperature materials. For more detailed design of the experimental setup, the initial inhomogeneous porous structure of the foam target should be taken into account. In relation to future WDM experiments, Zylstra et al. conducted a numerical study on the hydrodynamic behavior and homogenization of Van der Waals foams heated by pulsed heavy-ion beams [6]. In their calculation, however, the dependence of the projectile stopping on temperature and density mentioned above is not taken into account.

In this paper we present results of numerical study on the heavy-ion stopping in foam targets with subcell-scale hydro motions induced by the energy deposition of incident ions themselves. Calculation of the projectile energy loss taking into account the target temperature- and density dependence is briefly introduced. The results on the energy loss profile are compared with those for the homogeneous equivalent target in consideration of the density- and temperature distribution during irradiation.

2. Method of calculation

To simulate a porous foam target, we employed a simple 1D periodic multilayer model consisting of thin solid slabs and gaps between them, like in Ref. [6]. This model is illustrated in Fig. 1.

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http://dx.doi.org/10.1016/j.nima.2013.05.104

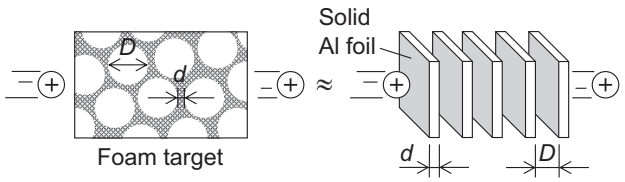

Fig. 1. 1D multilayer structure simulating a foam target.

The averaged pore diameter and cell-wall thickness of the foam were represented by the gap width between the slabs and the slab thickness, respectively. Residual gases in the pores were simulated by dilute ($\rho=10^{-3}\rho_{\rm solid}$) vapor of the wall material. Note that the present method has a limitation that the multidimensional mixing due to hydrodynamic instability cannot be treated, and therefore homogenization is underestimated. Thus, in this paper, only the upper limit of the above effect can be discussed.

In this work, changes of stopping cross-section due to changes in atomic size (Wigner–Seitz radius), excitation, and ionization due to changes in the target condition during heating and expansion must be taken into account in the calculation. To assess the target condition, we used the phase space density distribution of electrons in the target atoms evaluated by a finite-temperature Thomas–Fermi model with given Wigner–Seitz radii corresponding to given atomic densities. A simple binary encounter model [7] was employed to calculate the total electronic stopping cross-section S_e by integrating the energy transfer from the projectile to each target electron. The projectile charge was evaluated using a simple Thomas–Fermi scaling [8]. The total cross-section S was obtained as $S=S_e+S_n$, where S_n denotes the nuclear stopping cross-section [9].

We tested a combination of $_{11}$Na projectiles and subrange $_{13}$Al foam targets with $\rho=0.05\rho_{\rm solid}$. The incident projectile energy was adjusted so that the Bragg peak could be at the center of the target [5]. For this adjustment, as has been done in previous studies, the stopping power data for room-temperature solid-density Al was used. The hydrodynamic motion of the multilayer target was calculated with a 1D computer code MULTI [10]. We assumed that the targets are irradiated by a pulsed beam with a temporal flux profile $\phi(t)=\phi_0\sin^2(\pi t/\tau)$ $(0<t<\tau$, otherwise $\phi(t)=0)$. The pulse duration τ and the peak flux ϕ_0 are 2 ns and 4 GW/mm^2, respectively. It follows that the total energy deposition $\phi_0\tau/2$ is 4 J/mm^2.

3. Results and discussion

3.1. Temperature- and density-dependent ion stopping

Fig. 2(a) shows the stopping cross-section calculated for solid density targets as a function of the projectile energy for different temperatures. Even if the target is heated up to 10 eV, we see practically no change of the Bragg curve. In this figure, well-established data [11] for solid-density room-temperature Al target are plotted for comparison. The shape of the calculated curves including the Bragg peak agrees well with that of the previous data.

Fig. 2(b) shows the results for $\rho=0.03\rho_{\rm solid}$ targets. The stopping cross-section increases with the target temperature, especially at low projectile energies. Also the Bragg-peak position shifts slightly toward the low energy. This result is explained by the increase of the low velocity portion of the bound electrons due to excitation. At higher temperatures, a small bump appears in the low velocity region corresponding to the thermal speed of electrons. This bump is attributed to the enhanced stopping by free electrons which has been observed in highly ionized plasma targets [1–3]. The data of stopping cross-sections calculated for 0.025 eV≤kT≤10 eV and $10^{-4}\rho_{\rm solid}\le\rho\le10\rho_{\rm solid}$ were embedded in the hydrodynamics code.

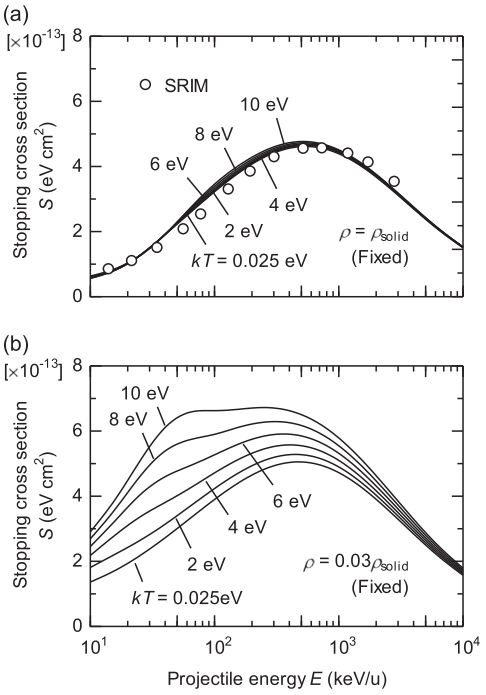

Fig. 2. Stopping cross-section as a function of the projectile energy for different target temperatures and densities.

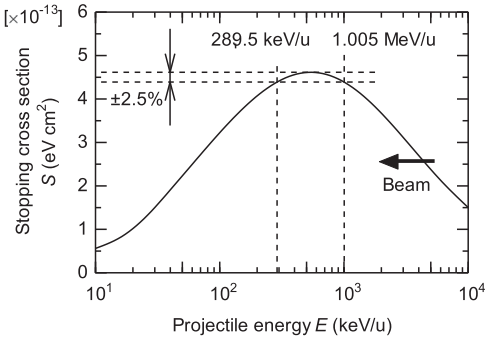

Fig. 3. Determination of the target thickness and the projectile energy for given homogeneity of specific energy deposition profile in the depth direction.

3.2. Determination of the target mass thickness

From the curve for $kT=0.025$ eV in Fig. 2(a), by ignoring the temperature- and density dependence of the stopping cross-section, we determined an appropriate combination of target mass thickness and incident projectile energy to achieve an energy deposition profile with a given required homogeneity. The procedure is shown in Fig. 3. We assumed that the limit of acceptable inhomogeneity is $\pm2.5\%$. In this case the incident energy $E_{\rm in}$ and the exit energy $E_{\rm out}$ are automatically determined to be 1.01 MeV/u and 0.29 MeV/u, respectively. The corresponding energy deposition in the target is $\Delta E\equiv E_{\rm in}-E_{\rm out}=16.5$ MeV, which is 71% of the incident projectile energy. By integrating $1/S$ from $E_{\rm in}$ to $E_{\rm out}$, the target areal thickness was determined to be 3.72×10^{19} cm^{-2}, which corresponds to 123 μm for the $\rho=0.05\rho_{\rm solid}$ Al target.

3.3. Target hydrodynamics and the projectile stopping

Fig. 4(a) and (b) shows streak images of the density- and the temperature profiles for the foam target with seven layers. The wall thickness d and the gap between adjacent walls D are 0.9 μm and 20 μm, respectively. The results for a homogeneous target with the