

Evolution of the energy distribution of ions moving in aluminum targets[☆]

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Abstract

The dynamics of ions moving in thin foils and underdense foams will play a key role in the design of future warm dense matter experiments. Using the SRIM code, we estimate that for initially mono-energetic 2.8 MeV Li⁺ ions hitting a solid density Al foil, the induced energy spread due to stochastic effects is 10% at a depth of 3.4 μm. In contrast, for 400 keV K⁺ ions hitting an Al foam of 10% solid density, stochastic effects induce a nearly 100% energy spread. At these beam energies, the nuclear stopping effects are negligible for the Li beam, but not for the K beam. We estimate this stochastic energy spread leads to almost no change in uniformity of temperature for the target heated by the Li beam, but leads to a factor of two of non-uniformity in temperature of the target for the K beam over a depth of 3.4 μm. One application of these new results for temperature profiles with realistic beam energy distributions is as input to hydrodynamic simulations of the evolution of the target.

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1. Introduction

Ion beam accelerators have been used to produce High Energy Density (HED) states in the laboratory. Experiments at The Gesellschaft für Schwerionenforschung (GSI) Darmstadt [1] have demonstrated that these interesting states of matter can be achieved by using very high energy beams to heat targets in the laboratory. The recent HEDP workshop [2] is an indication that there is currently strong interest in the United States in producing HED states in the laboratory, especially if it is shown to be feasible to use existing or proposed accelerators that are significantly lower energy than those produced at GSI. Ion beam drivers

have two main advantages over conventional (LASER and X-ray) drivers for the production of HED states: (i) ion beams can heat target samples uniformly, making them capable of exploring areas of equation-of-state space off the shock curves, and (ii) ion beams can heat macroscopic sample sizes, making diagnostics easier.

The degree to which ion beams can heat samples uniformly depends on the ion dynamics within the samples. Beam energy is the primary factor that determines the rate at which energy is deposited in the target. One strategy to achieve uniform heating is to tune the beam energy to be well above the Bragg peak, so that the stopping power, dE/dx , is essentially constant. HED experiments at GSI operate in this regime, with beam energies up to a few hundred MeV/u, and proposed beams at the FAIR facility of up to a few GeV/u [3].

Moderate energy ion beams may also be used to generate HED states. It has been shown [4] that high uniformity of energy deposition can be achieved by choosing a beam energy and target thickness such that beam ions enter the

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target slightly above the Bragg peak, and exit below the peak. This is the strategy that is used in the proposed Neutralized Drift Compression Experiment 2 (NDCX 2) facility [5] as is described below.

Current experiments which operate below the Bragg peak, such as the current NDCX facility [6] at the Lawrence Berkeley National Laboratory (LBNL), may also be candidates for HED drivers. One effect that could degrade the uniformity of the heating in this experiment is the stochastic nature of the beam interaction with the target nuclei (straggling) as it moves through the target. The proposed HED experiment at the NDCX will operate in a regime where nuclear stopping is significant, and so straggling is expected to be important. In contrast, nuclear stopping is not significant at and above the Bragg peak.

The purpose of this paper is to estimate the magnitude of the effect of straggling for two cases: the first case is a 2.8 MeV Li^+ beam striking a solid density Al target, which is a candidate for the beam at the NDCX 2 HED experiment. The second case is a 400 keV K^+ beam striking a 10% solid density Al foam target, corresponding to the current beam at the NDCX experiment. In the experiment with the Li beam, researchers believe the foil thickness could be about $3.6\ \mu\text{m}$, while the foam in the experiment with the K beam would be $\sim 3\text{--}10\ \mu\text{m}$. Using the SRIM code [7], we estimate that for the Li beam, the induced energy spread due to stochastic effects is about 10% after passing through $3.4\ \mu\text{m}$ of solid density Al. In contrast, for the K^+ beam, stochastic effects induce a nearly 100% energy spread in the same distance. We estimate this stochastic energy spread leads to almost no change in uniformity of temperature for the target heated by the Li beam, but leads to a factor of two of non-uniformity in temperature of the target for the K beam over a depth of $3.4\ \mu\text{m}$. One application of these new results for temperature profiles with realistic beam energy distributions is as input to hydrodynamic simulations of the evolution of the target.

2. Results

To estimate stochastic energy spread effects, we use SRIM to simulate a beam of initially mono-energetic ions impacting aluminum targets at normal incidence. SRIM includes the ability to track individual ions as they undergo both longitudinal and lateral scattering. We followed the evolution of 10,000 incident ions to limit statistical errors to the order of one percent.

Fig. 1 shows the simulation results for 2.8 MeV Li^+ on a solid Al foil. In this case, the induced spread of energy at a depth of $3.4\ \mu\text{m}$ is about 100 keV (roughly 10% of the mean beam energy of just over 900 keV). The induced energy spread is approximately constant throughout the entire depth of the foil. As shown in Fig. 2, the nuclear contribution to the stopping of Li in Al over the energies 0.9–2.8 MeV, is more than two orders of magnitude less than the electronic contribution. Because projectile collisions with target nuclei are the main source of straggling,

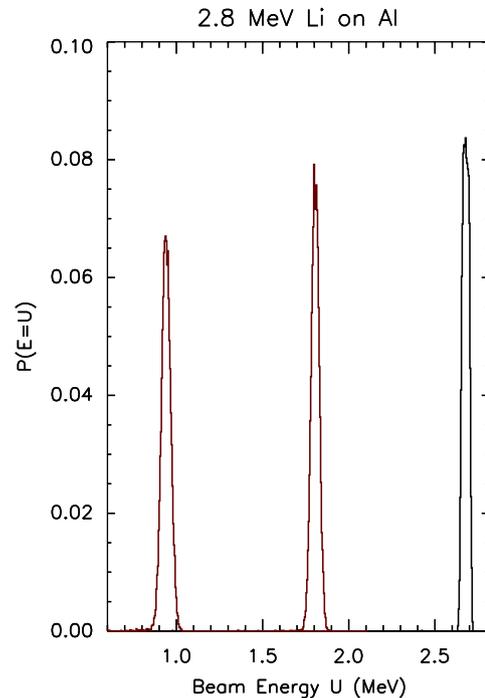


Fig. 1. Induced distribution of energies for 2.8 MeV Li^+ ions at depths of 0.2, 1.8, and $3.4\ \mu\text{m}$ in a solid density Al foil. The relatively small (roughly 10%) energy spread induced over the $3.4\ \mu\text{m}$ is due to a small nuclear component to the stopping power at these energies.

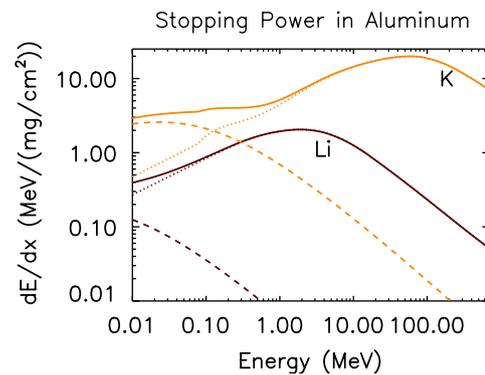


Fig. 2. Stopping power for lithium (brown lines) and potassium (yellow lines) in aluminum. Dashed lines are nuclear stopping, dotted lines are electronic stopping, and solid lines are total stopping powers. The units for stopping power are scaled by the density, so the stopping powers are valid for all densities of target, including solid and foam. The fraction of the stopping due to nuclear stopping is a measure of the amount of energy spread one can expect.

the induced energy spread in the beam is small in this case. Another quantitative measure of the energy spread is the number of projectile ions that have lost all their energy. In this case, less than 1.6% of the ions have lost all their energy after traveling $3.4\ \mu\text{m}$.

Fig. 3 shows the results for 400 keV K^+ on an Al foam of 10% solid density. In this case, at a depth of $3.4\ \mu\text{m}$, the induced energy spread is nearly 100% of the beam energy

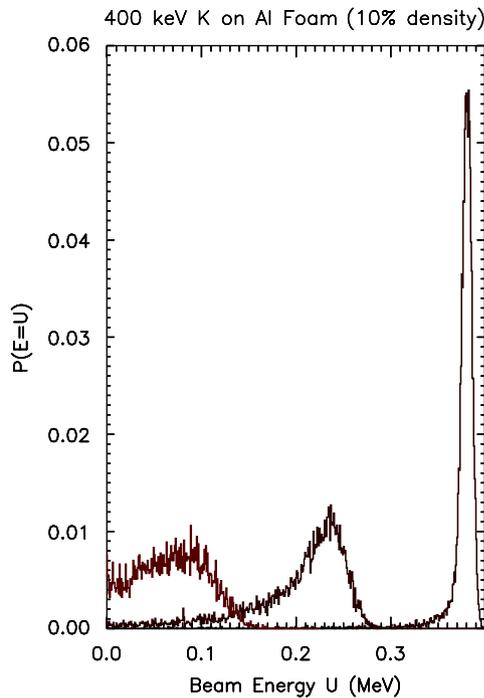


Fig. 3. Induced distribution of energies for 400 keV K^+ ions at depths of 0.2, 1.8, and 3.4 μm in a 10 μm , 10% solid density Al foam. The large (nearly 100%) energy spread induced over the 3.4 μm is due to a large nuclear component to the stopping power at these energies.

of roughly 100 keV. As seen in Fig. 2, the nuclear contribution to the stopping here makes up approximately 30–50% of the total stopping. This in turn results in the large energy spread seen in the simulations.

For this case, about half of the beam ions have come to rest before reaching a depth of 3.4 μm , which is close to the projected range of 3.6 μm for 400 keV K^+ ions in a 10% density foam. Approximately 70% of the beam ions come to rest by a depth of 4 μm .

Of primary interest here is how induced energy straggling effects the uniformity of target heating. For lithium there is no significant difference in the predicted temperature between the mono-energetic case and the case including the effects of stochastic deposition of energy, over a depth of 3.4 μm , as shown in Fig. 4. Both estimates predict a temperature of roughly 3.0 eV for this case. In contrast, target heating is less uniform for potassium when straggling is included. The mono-energetic beam assumption predicts a temperature of 0.075–0.1 eV, while the warm beam method predicts a temperature of 0.025–0.1 eV, as shown in Fig. 5. In addition, heating is seen beyond the projected range of the potassium ions because some ions stochastically travel farther than the projected range. In Figs. 4 and 5 the lines represent the temperature as a function of depth predicted assuming a mono-energetic beam and using the stopping powers shown in Fig. 2. Symbols are the temperature predicted using the evolving energy distributions of the beam when straggling is included, as shown in Figs. 1 and 3. One application of

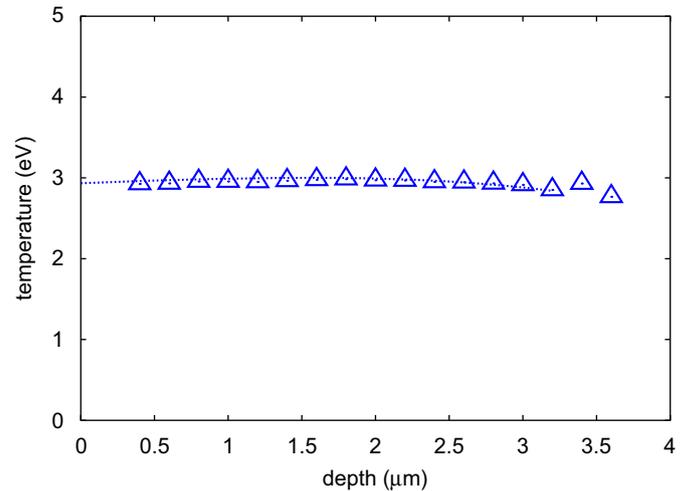


Fig. 4. Temperature profiles as a function of penetration depth for 2.8 MeV Li^+ ions in a solid density Al foil. The line is the temperature expected for a mono-energetic beam, while the symbols represent the temperature including the effects of the induced energy spread. Due to the relatively small energy spread in the Li beam, there is little difference between the temperature estimate assuming a mono-energetic beam and taking into account warm beam effects. Both estimates predict a temperature of roughly 3.0 eV for this case.

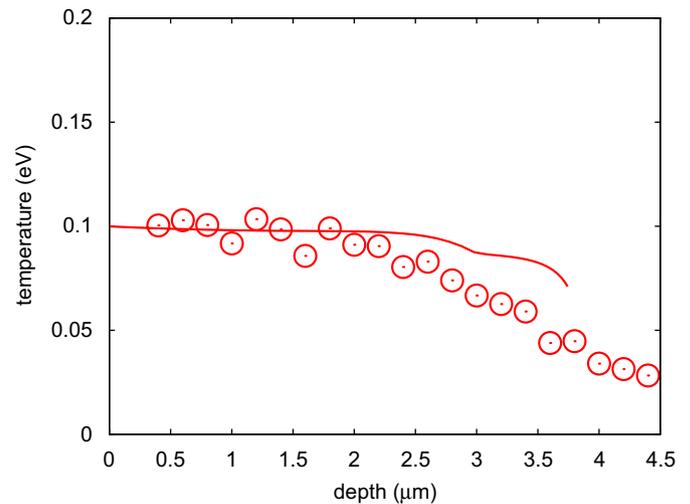


Fig. 5. Temperature profiles as a function of penetration depth for 400 keV K^+ ions in a 10% solid density Al foam. The line is the temperature expected for a mono-energetic beam, while the symbols represent the temperature including the effects of the induced energy spread. Due to the relatively large energy spread as the K beam gets further into the target, there is increasing disagreement between the temperature predicted assuming a mono-energetic beam and taking into account warm beam effects. The mono-energetic beam assumption predicts a temperature of 0.075–0.1 eV, while the warm beam method predicts a temperature of 0.025–0.1 eV. The warm beam assumption also predicts target heating deeper into the target than one would predict with a mono-energetic beam.

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