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Tunable proton stopping power of deuterium-tritium by mixing heavy ion dopants for fast ignition

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ABSTRACT

The theoretical model of charged-particle stopping power for the Coulomb logarithm $\ln\Lambda_b \geq 2$ plasma [Phys. Rev. Lett., 20, 3059 (1993)] is extended to investigate the transport of the energetic protons in a compressed deuterium-tritium (DT) pellet mixed with heavy ion dopants. It shows that an increase of mixed-ion charge state and density ratio results in the substantial enhancement of the proton stopping power, which leads to a shorter penetration distance and an earlier appearance of the Bragg peak with a higher magnitude. The effect of hot-spot mix on the proton-driven fast ignition model is discussed. It is found that ignition time required for a small mixed hot-spot can be significantly reduced with slightly increased beam energy. Nevertheless, the ignition cannot maintain for a long time due to increasing alpha-particle penetration distance and energy loss from mechanical work and thermal conduction at high temperatures.

1. Introduction

Fast ignition (FI) approach, as an alternative scheme to the conventional central spark ignition, has been proposed in order to reduce the required ignition energy, maximize energy gain and relax the symmetry requirement of implosion compression [1]. Laser-driven FI has two main routes, including hole boring [1,2] and cone-guided ignition [3,4]. Each involves the stable transport and efficient energy deposition of the charged particles in fusion capsule, which is crucial for the ignition. Unfortunately, using relativistic electron beams as an injected trigger, the energy conversion efficiency from the laser to the core is usually less than 50% [5]. Especially for the electron beams with large divergences, it reduces to 10% or even lower [6]. Furthermore, the beam filamentation and other instabilities are easily excited during propagating in fusion pellets [7,8]. Since the experimental observation of the laser-driven proton or ion beams based on target normal sheath acceleration mechanism (TNSA) [9], a concept of proton driven FI [4] is soon proposed. In principle, proton or ion beams have advantages of stiffer (i.e., an almost straight trajectory) beam transport and more localized energy deposition into the pellet core [4,10]. More impressive is that the favorable Bragg peak is appeared at the end of their paths [11].

The stopping power of energetic ions transporting in the DT fuel has attracted much attention in the past decades. Previous results [12-15] based on the Fokker–Planck equation (FP) strongly depend on the fundamental assumption of the Coulomb logarithm $\ln\Lambda_b \geq 10$, which severely limited their applications in the FI field ($1 \leq \ln\Lambda_b \leq 12$). Besides, it has been demonstrated that the large-angle scattering is also important when $\ln\Lambda_b$ is of order 1 [16]. Li and Petrasso (LP) model [16] properly treated the effects of large-angle scattering, small-angle collisions, collective plasma oscillations as well as quantum effects by the generalization of FP, which can be applicable to $\ln\Lambda_b \geq 2$ plasma. In what follows, we use this model to study the proton transport in a DT target mixed with heavy ion dopants. It is shown that the stopping power can be significantly enhanced with the increase of ionic charge state and density ratio. The proton penetration distance is thus substantially reduced and the Bragg peaks with high magnitudes are earlier appeared at the end of their paths, leading to a highly localized energy deposition. The effect of hot-spot mix on proton-driven FI is then discussed. When a small hot-spot mixed is employed, the required ignition time is shortened with slightly increased beam energy. But the ignition will quickly quench after a short time because alpha (α) particles cannot effectively deposit their energies into hot-spot fuel at higher temperatures, and the energy loss from mechanical work and thermal conduction is also of particular importance.

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2. Tunable proton energy loss of DT fuel mixed with heavy ion dopants

In the LP model, the stopping power of charged particles transporting in a fully ionized plasma is given by [16,17]

$$\frac{dE^{t/f}}{dx} = -\frac{2\pi n_f Z_t^2 Z_f^2 e^4}{E_t}\cdot\frac{m_t}{m_f}\cdot\left\{\left[-\left(1+\frac{m_t}{m_f}\right)\frac{2}{\sqrt{\pi}}\sqrt{x^{t/f}}+\mathrm{erf}\left(\sqrt{x^{t/f}}\right)\right]\ln\Lambda_{bf} + \frac{m_f}{m_t}\mathrm{erf}\left(\sqrt{x^{t/f}}\right)\Theta(x^{t/f})\ln\left(1.123\sqrt{x^{t/f}}\right)\right\} \quad (1)$$

where $Z_t(Z_f)$ is the charge number of test (field) particle, e is the electron charge, E_t is the kinetic energy of test particle, n_f is the number density of field particle, $m_t(m_f)$ is the mass of test (field) particle. $x^{t/f} = (m_f E_t)/(m_t T)$, $\mathrm{erf}(x) = \left(2/\sqrt{\pi}\right)\int_0^x \exp(-t^2)dt$ is the error function, and T is the plasma temperature. The Coulomb logarithm $\ln\Lambda_{tf}$ for the test-field particle interaction is $\ln\sqrt{\sqrt{T^2+\varepsilon_F^2}/4\pi e^2 n_e \sqrt{p_\perp^2 + (\hbar/2m_r u)^2}}$ for field electrons and $\ln\sqrt{T/4\pi e^2 n_i p_\perp}$ for field ions, respectively. Here $\varepsilon_F = 0.3646\left(n_e/10^{21}\,\mathrm{cm}^{-3}\right)^{2/3}$ is the Fermi energy of electrons, $p_\perp = Z_t Z_f e^2/m_r u^2$, $m_r = m_t m_f/(m_t+m_f)$, $u \simeq \sqrt{v_t^2+v_f^2}$, and $v_t(v_f)$ is the velocity of test (field) particle. $\Theta(x)$ is the step function whose value is 0 for $x \le 1$ and 1 for $x \ge 1$, the term $\ln\left(1.123\sqrt{x}\right)$ is the contribution of collective effect. Thus, the total stopping power should be $dE/dx = \sum_f \left(dE^{t/f}/dx\right)$ and the distance that a test particle slows down to the residual energy E can be calculated by $x(E, E_t) = \int_{E_t}^{E}(dE/dx)^{-1}dE$. In particular, $x(0, E_t)$ corresponds to the penetration distance of test particle $R = \int_{E_t}^{0}(dE/dx)^{-1}dE$ when E reduces to 0.

Table 1
The charge state and atomic number of different mixed-ion species.

M	N	Be	Al	Cu	Ag	Au
Z_M	0	4	13	29	47	79
A_M	0	9	27	63.5	108	197

Here we consider the proton (test particle, p) stopping process in the mixture of DT (field particles, e, D and T) plasma fuel and heavy ion dopant (field particle, e and M). Taking the DT fuel density 300 g/cm^3, typical of the FI approach, the number density should be $n_D = n_T = 3.6\times10^{25}\ \mathrm{cm}^{-3}$ when the optimal composition density ratio $n_D/n_T = 1$ is chosen. The number density of heavy ions is $n_M = \xi_M n_D$, where the parameter ξ_M is the mixed density ratio. The total electron number density can thus be obtained by $n_e = (2 + Z_M\xi_M)n_D$ according to the charge neutrality, where Z_M is the ionic charge state of the mixed dopant. The respective charge and atomic numbers of different mixed ion species are listed in Table 1, where N represents the pure DT fuel case for comparison.

Fig. 1a shows the proton stopping power resulting from the plasma ions (D, T and M) dE^i/dx as a function of the incident proton energy E_p for different mixed-ion species (M). One can see that, with an increase of Z_M or A_M (from N to Au), dE^i/dx increases significantly for a constant mixed ratio. Meanwhile contributions of these

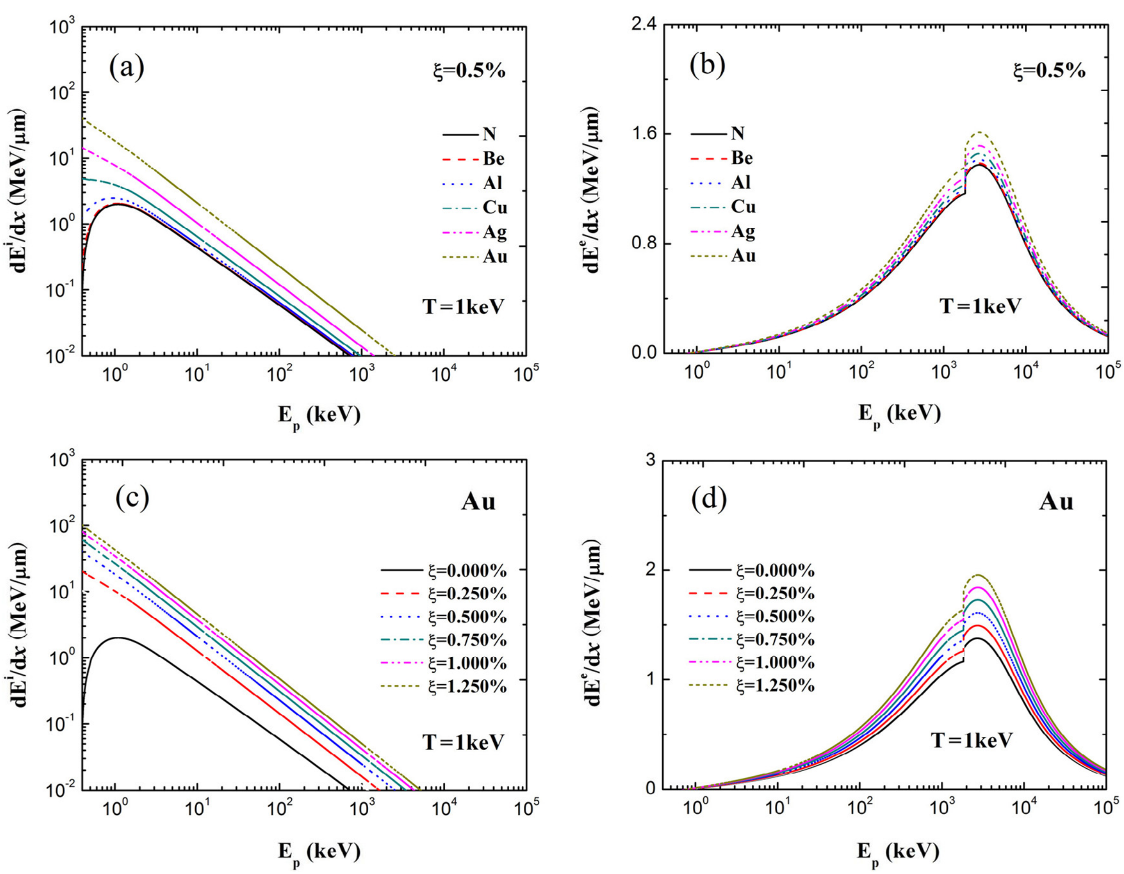

Fig. 1. Proton stopping power in a full-ionized DT + M plasma. Contributions from the plasma ions (a) dE^i/dx and electrons (b) dE^e/dx for different ion species with $\xi_M = 0.5\%$; Contributions from the plasma ions (c) dE^i/dx and electrons (d) dE^e/dx for different density ratios in DT + Au plasma. The temperature is $T = 1$ keV, and the number densities of D and T ions are set as $3.6\times10^{25}\ \mathrm{cm}^{-3}$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)