Measurements of Ion Stopping Around the Bragg Peak in High-Energy-Density Plasmas

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(Received 14 April 2015; published 9 November 2015)

For the first time, quantitative measurements of ion stopping at energies around the Bragg peak (or peak ion stopping, which occurs at an ion velocity comparable to the average thermal electron velocity), and its dependence on electron temperature \(T_e\) and electron number density \(n_e\) in the range of 0.5–4.0 keV and \(3 \times 10^{22}\) to \(3 \times 10^{23}\) \(\text{cm}^{-3}\) have been conducted, respectively. It is experimentally demonstrated that the position and amplitude of the Bragg peak varies strongly with \(T_e\) with \(n_e\). The importance of including quantum diffraction is also demonstrated in the stopping-power modeling of high-energy-density plasmas.

DOI: 10.1103/PhysRevLett.115.205001

A fundamental understanding of DT-alpha stopping in high-energy-density plasmas (HEDP) is essential to achieving hot-spot ignition at the National Ignition Facility (NIF) [1]. This requires accurate knowledge about the evolution of plasma conditions and the DT-alpha transport and energy deposition in plasmas for a wide range of electron \((T_e)\) and ion temperatures \((T_i)\) spanning from tens of eV to tens of keV, and electron number densities \((n_e)\) from \(\sim 10^{21}\) to \(\sim 10^{20}\) \(\text{cm}^{-3}\).

Over the last decades, ion stopping in weakly coupled to strongly coupled HEDP has been subject to extensive analytical and numerical studies [2–10], but only a limited set of experimental data exists to validate these theories. Most previous experiments also used only one type of ion with relatively high initial energy, in plasmas with \(n_e < 10^{23}\) \(\text{cm}^{-3}\) and \(T_e < 60\) eV [11–21]. In addition, none of these experiments probed the detailed characteristics of the Bragg peak (or peak ion stopping), which occurs at an ion velocity comparable to the average thermal electron velocity.

To determine the energy lost by the four ions as they traversed the plasma, energy spectra of the emitted ions were measured simultaneously with two magnet-based charged-particle spectrometers (CPS1 and CPS2) [28]. Six wedge-range-filter proton spectrometers [28] positioned at various locations around the implosion were also used to measure \(\text{D}^3\text{He}-\text{proton} spectrum. An example of spectra measured with CPS2 for two implosions, with similar total areal-density \((\rho R)\) values [29], where most of the energy loss took place in the cold remaining glass shell (blue spectra) and in the hot \(\text{D}^3\text{He} \text{fuel} \text{(red spectra)} is shown in Fig. 1. By contrasting the measured mean energies, indicated in Fig. 1, to the birth energies of the ions (temperature corrected), an average energy loss \((-\Delta E_i)\) was determined and used to assess the plasma stopping power. As shown in Fig. 1, the DD tritons, DD protons, and \(\text{D}^3\text{He} \text{alphas display significantly larger} -\Delta E_i\) in the cold plasma than in the hot plasma. The \(\text{D}^3\text{He} \text{protons, on the other hand, exhibit a similar} -\Delta E_i\) in these two plasmas, as they probe plasma stopping at velocities

\[
\text{D} + \text{D} \rightarrow t(1.01 \text{ MeV}) + p(3.02 \text{ MeV}),
\]

\[
\text{D} + \text{He} \rightarrow \text{He}(3.71 \text{ MeV}) + p(14.63 \text{ MeV}),
\]

where the birth energies shown in the parentheses are for a “zero temperature” plasma [23]. From the observed energy losses of these ions, Hicks et al. were able to describe qualitatively the behavior of the ion stopping for one plasma condition. The work described here makes significant advances over previous experimental efforts, by quantitatively assessing the characteristics of the ion stopping around the Bragg peak for different HEDP conditions. This was done through accurate measurements of energy loss of the four ions, produced in reactions (1) and (2).
For the other implosions, the energy loss took place mainly in the hotter D, where the energy loss mainly occurred. For implosion 29828, the energy loss took place mainly in the colder glass-shell plasma, while for the other implosions, the energy loss took place mainly in the hotter D³He plasma.

Table I. Capsule and laser parameters for four selected implosions, and measured DD burned-averaged Tᵣ and determined key implosion parameters [nᵣ, Tᵣ, nₑ (nₑ ≈ 1.5nᵣ)], plasma-coupling parameter (Γ), degeneracy parameter (θ) [27] and total ρR, for the region where the energy loss mainly occurred. For implosion 29828, the energy loss took place mainly in the colder glass-shell plasma, while for the other implosions, the energy loss took place mainly in the hotter D³He plasma.

<table>
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<tbody>
<tr>
<td>27814</td>
<td>D³He(18 atm)SiO₂[2.3 μm] OD[948 μm]</td>
<td>1-ns square</td>
<td>8.4</td>
<td>3.7</td>
<td>2 x 10²¹</td>
<td>1.8</td>
<td>3 x 10²³</td>
<td>0.9</td>
<td>110</td>
<td>8.1</td>
</tr>
<tr>
<td>29828</td>
<td>D³He(18 atm)SiO₂[2.6 μm] OD[917 μm]</td>
<td>0.4-ns Gaussian</td>
<td>9.4</td>
<td>6.7</td>
<td>3 x 10²²</td>
<td>0.6</td>
<td>5 x 10²²</td>
<td>1.4</td>
<td>120</td>
<td>2.0</td>
</tr>
<tr>
<td>43233</td>
<td>D³He(18 atm)SiO₂[2.5 μm] OD[855 μm]</td>
<td>1-ns square</td>
<td>10.6</td>
<td>11.6</td>
<td>5 x 10²²</td>
<td>3.9</td>
<td>8 x 10²²</td>
<td>0.3</td>
<td>580</td>
<td>3.5</td>
</tr>
<tr>
<td>43235</td>
<td>D³He(18 atm)SiO₂[2.5 μm] OD[854 μm]</td>
<td>1-ns square</td>
<td>9.9</td>
<td>10.1</td>
<td>2 x 10²²</td>
<td>2.1</td>
<td>3 x 10²²</td>
<td>0.3</td>
<td>600</td>
<td>1.4</td>
</tr>
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Well above the Bragg peak. These differences are discussed in detail below. In addition, the uncertainties associated with the measured mean energies shown in Fig. 1, are mainly due to the spectrometer energy-calibration error (in some cases statistics also affects the uncertainties), which dictates the total uncertainty in the determined −ΔEᵢ.

To make use of the measured −ΔEᵢ and assess the plasma stopping power, it is necessary to determine the HEDP conditions through which the ions traversed. For each implosion, a Tᵣ and a DD yield were measured from the Doppler broadened neutron-time-of-flight signal [30]. A second measurement of Tᵣ was obtained for each implosion from the DD-D³He yield ratio, and the Tᵣ values and uncertainties used in this Letter are weighted averages of these two measurements. D³He and DD burn profiles were measured with the proton core imaging system [31], and the D³He and DD burn duration was measured with the particle temporal diagnostic and neutron temporal diagnostic (NTD) [32,33], respectively. A secondary-neutron yield relative to the primary neutron yield (Y₂n/Y₁n) was also measured for a D³He-fuel ρR determination [34].

For the eighteen implosions, the measured DD and D³He yield ranged from 2.0 × 10⁹ to 1.2 × 10¹⁰ and from 1.2 × 10⁹ to 1.3 × 10¹⁰, respectively; Tᵣ ranged from 2.7 to 11.6 keV; the DD- and D³He-burn duration both ranged from 150 to 180 ps; and the measured size of the DD- and D³He-burn profiles ranged from ∼45 to ∼100 μm and ∼30 to ∼60 μm (radius at 1/e relative to the peak intensity), respectively. Using 1D modeling of the implosion, involving a parabolic temperature profile and constant D³He-fuel density, a good match to these nuclear observables was found for average ion-number densities (nᵣ) ranging from 2 × 10²² to 2 × 10²³ cm⁻³ (nₑ ≈ 1.5nᵣ for these D³He plasmas). Tₑ could not be measured directly in these experiments, but was qualitatively and independently assessed from the nₑ, nᵣ, Tᵣ, and burn-duration data. A Y₂n/Y₁n ratio up to (3.96 ± 0.17) × 10⁻⁴ was measured, which corresponds to a D³He fuel ρR up to 7 mg/cm². The ρR of the remaining unablated shell was determined from benchmarked 1D simulations [35], which indicate that the fuel ρR is about an order of magnitude larger than the remaining-shell ρR for the implosions with a 1-ns laser-pulse drive, while the remaining-shell ρR dominates the D³He-fuel ρR for the implosions with a 0.4-ns laser pulse. As a consequence, the ion energy loss is mainly taking place in the D³He fuel in the 1-ns implosions and in the remaining unablated shell in the 0.4-ns implosions.

Although the HEDP conditions have been characterized, the information is not sufficient for distinguishing state-of-the-art plasma-stopping-power theories at vᵢ ~ vᵣe, i.e., at the Bragg peak, which is the long-term goal of this effort. For this, we need information on how the spatial profiles of nₑ and Tₑ vary in time during the nuclear production period. Instead, our aim is twofold. First, we simply aim to experimentally demonstrate that the amplitude of the position and amplitude of the Bragg peak varies strongly with Tₑ with nₑ. Second, as the impact parameter of the closest approach between the projectile ions and plasma electrons can be smaller than the de Broglie wavelength, we

FIG. 1 (color online). CPS2-measured spectra of DD tritons, D³He alphas, DD protons, and D³He protons produced in implosions 29828 (blue) and 43233 (red). These experiments were designed to generate similar total ρR values but to have most of the ion energy loss taking place in the cold remaining shell for implosion 29828 (blue spectra) and in the hot fuel for implosion 43233 (red spectra).
also aim to demonstrate the importance of including quantum diffraction in the stopping-power modeling of the ion energy loss at these HEDP conditions.

The Brown-Preston-Singleton (BPS) [4] and the Li-Petrasso (LP) stopping [5] formalisms were used to model the data. The BPS formalism includes a Coulomb logarithm in the weakly coupled limit, which is derived using the dimensional continuation method, and the LP stopping formalism is derived from a Fokker-Planck collision operator that uses an ad hoc Coulomb logarithm. Although these formalisms have limitations, they are used in this work to explore if the dominant physics is captured. Figure 2 illustrates the BPS (black solid) and LP (green solid) proton stopping curves, given in keV/(mg/cm^2), for a hypothetical uniform plasma that is representative for the HEDP conditions in these experiments. At \( v_i > v_{th} \), the BPS and LP formalisms predict similar charged-particle stopping, while there is \( \sim 20\% \) at \( v_i < v_{th} \). The BPS quantum (dotted black) and the BPS classical (dashed black) are also shown to illustrate their significance. For this plasma condition, the quantum reduction to the classical ion stopping is \( \sim 25\%-30\% \).

An effective way to evaluate the measured \( -\Delta E_i \) of ions with different birth energy \( (E_i) \), charge \( (Z_i) \), and mass \( (A_i) \) is to show the dependency between \( -\Delta E_i/Z_i^2 \) and \( E_i/A_i \). Presenting the data in this form, the ion energy loss is almost exclusively a function of \( v_i \) (any explicit dependence on \( A_i \) and \( Z_i \) is small and restricted to the slowly varying Coulomb logarithm) and can easily be analyzed using a plasma stopping-power model. Figures 3(a) and 3(b) illustrate the \( -\Delta E_i/Z_i^2 \) vs \( E_i/A_i \) dependence on \( T_e \). This data set was directly determined from the low-temperature and high-temperature data shown in Fig. 1. The black (green) curves are the BPS (LP) modeled fits to the data. These curves were obtained by integrating the plasma-stopping-power functions over assumed values of \( T_e \) and \( \rho R \), which were varied until best fits to the data were obtained. Clearly, these experimental results demonstrate that the plasma-stopping-power function varies with \( T_e \) in the framework of the BPS and LP formalisms. At \( T_e \) of \( \sim 0.6 \) keV \( (\Gamma = 1.4\% \); see Table I), the effective proton Bragg peak is 220 keV/(mg/cm^2), which is reduced to 40 keV per mg/cm^2 for a \( T_e \) of \( \sim 4 \) keV \( (\Gamma = 0.3\% \); see Table I). This reduction is caused by the fact that \( v_i \approx v_{th} \) for the DD tritons, D^3He alphas, and DD protons in the low-temperature case, while \( v_i < v_{th} \) for these ions in the high-temperature case. This agrees with theories in which the Bragg peak scales with \( 1/T_e \). The average energy loss of the D^3He protons is, on the other hand, unaffected by an increasing \( T_e \) because \( v_i > v_{th} \). In contrast, the two data sets shown in Figs. 4(a) and 4(b) illustrate the \( -\Delta E_i/Z_i^2 \) vs \( E_i/A_i \) dependence on \( \rho R \) (or \( n_e \) [29]), which indicates that the D^3He-proton energy loss increases with increasing \( \rho R \) with \( \sim 40 \) keV/(mg/cm^2).

To fully constrain and validate the stopping-power formalisms used to model this type of data, an independent measurement of \( T_e \) and \( \rho R \) (or \( n_e \)) must be made. In these experiments, \( T_e \) could not be measured directly, but a D^3He fuel \( \rho R \) was determined from the measured \( Y_{2\alpha}/Y_n \) ratio for most implosions. In the case of the high-\( \rho R \) implosion shown in Fig. 4(b) (implosion 27814), a \( Y_{2\alpha}/Y_n \) ratio of \( (3.96 \pm 0.17) \times 10^{-4} \) was measured, which corresponds to a D^3He-fuel \( \rho R \) of 7.1 \( \pm 0.3 \) mg/cm^2. According to benchmarked 1D-implosion simulations, this represents 88% of the total \( \rho R \) of 8.1 \( \pm 0.3 \) mg/cm^2 (D^3He fuel \( \rho R \) + glass shell \( \rho R \)). Figure 5 shows the high-\( \rho R \) implosion data contrasted to BPS and LP modeling that uses the fixed \( \rho R \) value of 8.1 mg/cm^2 and a varying \( T_e \) to minimize the reduced \( \chi^2 \). For comparison, BPS modeling of the data was also done when the quantum component was switched off. Here, the inferred \( T_e \) is dictated mainly by the energy loss.

FIG. 2 (color online). Brown-Preston-Singleton (BPS) and Li-Petrasso (LP) modeling of proton stopping in a uniform plasma with a \( T_e \) of 1.0 keV and \( n_e \) of \( 5 \times 10^{22} \) cm\(^{-3} \). The BPS quantum (dotted black) and BPS classical stopping (dashed black) are also shown.
discrepancies for of the DD tritons, D represent the BPS (LP) modeling. For the low-
was similar in these experiments. The black (green) curves
including quantum diffraction in the plasma-stopping-
overpredicts the ion stopping, indicating the importance of
and its uncertainty alone. We find that classical BPS theory
be experimentally inconsistent with the
As a consequence, the classical modeling can be shown to
...The work described herein was performed in part at the
LLE National Laser User’s Facility (NULF), and was
supported in part by U.S. DOE (Grant No. DE-FG03-
03SF22691), LLNL (subcontract Grant No. B504974), and
LLE (subcontract Grant No. 412160-001G). In addition,
P.E.G. acknowledges support from the Laboratory
Directed Research and Development Program at LLNL
under tracking code No. 12-SI-005.

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[2] T. A. Mehlhorn, A finite material temperature model for ion
energy deposition in ion driven inertial confinement fusion

[3] T. Peter, and J. Meyer-ter-Vehn, Energy loss of heavy ions in
dense plasma. I. Linear and nonlinear Vlasov theory for the

particle motion in a highly ionized plasma, Phys. Rep. 410,

Powers in Inertial Confinement Fusion Plasmas, Phys.
For a finite temperature, the mean energy of the fusion products is slightly upshifted by a few tens of keV [22].