Effects of scattering upon energetic ion energy loss in plasmas*

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The effects of scattering are assessed for energetic ions of interest as ρR, yield, and/or implosion symmetry diagnostics. Because the Coulomb logarithm between such energetic ions ($\gtrsim 1$ MeV) and the *"field"* ions is always of order 10 or larger, scattering effects are shown to be small. In contrast the Coulomb logarithm between energetic ions and *"field"* electrons is typically of order 5; but here the large mass ratio (10^4) between ion and electron precludes the possibility of ion scattering. Consequently the continuous-slowing-down stopping power and the linear-energy-transfer (LET) stopping power are very close. The consequences of this near identity in the stopping powers is exploited in order to calculate ρR over a range of plasma parameters of relevance to inertial confinement fusion (ICF) plasmas. © *1995 American Institute of Physics.*

I. INTRODUCTION

For inertially confined fusion plasmas, energetic ions generated from knock-on, secondary, and primary fusion reactions (Table I), offer diagnostic capabilities of fuel ρR[1-7] and of implosion symmetry and yield.[8,9] In particular, with the new charged-particle spectrometer proposed by Hicks *et al.*[8,9] (Fig. 1), sensitive measurements of charged particles with energies from ~0.2 MeV to 18 MeV are now feasible. Especially because of the spectrometer's unique low-energy sensitivity, measurements of fuel ρR's as large as ~0.3 g/cm² seem readily possible. In contrast, previous charged-particle spectrometers typically had a low-energy cutoff of about 4 MeV.[3] However, among other important issues (such as pusher ρdR energy degradation), the effects of ion scattering upon the linear-energy transfer (LET) of the energetic ions—be they knock-ons, secondaries, or primaries—need to be addressed in order to more fully assess the practical realization of this diagnostic. For example, Nakaishi *et al.*[4] claim that for ρR diagnostics, the effects of scattering need to be carefully treated. They in fact develop a Monte Carlo approach in assessing such effects. Our analysis indicates that for all energetic charged particles of interest—protons, deuterons, and tritons—scattering effects can be ignored.

II. ANALYSIS

Herein we utilize recent calculations that allow one to readily assess the effects of scattering that could occur in dense, moderately coupled plasmas. We find there is little difference between the continuous-slowing-down stopping power of Ref. 10, which does include some effects due to scattering, and the linear-energy-transfer stopping power. The essence of the argument is based on the following two facts. First, the energetic ions (the so-called "test" particles) almost exclusively lose energy to the plasma *"field"* electrons. And second, because the Coulomb logarithm for the

energetic ions and *"field"* ions is always of order 10 or larger, scattering effects can be shown to be small [see Eq. (1)]. This is also qualitatively reflected by the circumstance that for "test" and "field" particles of comparable mass, the Coulomb logarithm is a measure of the importance of small-angle collisions to that of scattering.[10] In contrast, the Coulomb logarithm between "test" ions and "field" electrons is of order 5 (Fig. 2); however, because of the huge mass difference between "test" ions and "field" electrons (~10^4), scattering of the energetic ions off the "field" electrons is precluded.

In subsequent discussion, we utilize the stopping power of Refs. 10 and 11:

$$\frac{dE^{t/f}}{dx} = -\frac{(Z_t e)^2}{v_t^2}\,\omega_{pf}^2 G(x^{t/f})\ln \Lambda_b,\tag{1}$$

where $dE^{t/f}/dx$ is the stopping power of a test particle (subscript or superscript t) in a field of background charges (subscript or superscript f) and

$$G(x^{t/f}) = \mu(x^{t/f}) - \frac{m_f}{m_t}\left[\frac{d\mu(x^{t/f})}{dx^{t/f}} - \frac{1}{\ln \Lambda_b}\right.$$
$$\left. \times \left(\mu(x^{t/f}) + \frac{d\mu(x^{t/f})}{dx^{t/f}}\right)\right].\tag{2}$$

The contribution of large-angle scattering is solely manifested by $1/\ln \Lambda_b$ terms of Eq. (2). In particular, if $\ln \Lambda_b \gtrsim 10$ and we ignore this correction, then Eqs. (1) and (2) reduce to Trubnikov's expression.[12] In the above equations, $Z_t e$ is the test charge; v_t (v_f) is the test (field) particle velocity with

TABLE I. Source of energetic ions.

Primary fusion reaction	$D+D \rightarrow T+p(3.02$ MeV$)$
	$D+{}^3\mathrm{He} \rightarrow \alpha(3.6$ MeV$)+p(14.7$ MeV$)$
Secondary fusion reaction	${}^3\mathrm{He}(0.82$ MeV$)+D \rightarrow \alpha+p(12.5-17.4$ MeV$)$
14.1 MeV neutron knock-ons	$p+n(14.1$ MeV$)\rightarrow p(\lesssim 14.1$ MeV$)+n'$
	$D+n(14.1$ MeV$)\rightarrow D(\lesssim 12.5$ MeV$)+n'$
	$T+n(14.1$ MeV$)\rightarrow T(\lesssim 10.6$ MeV$)+n'$

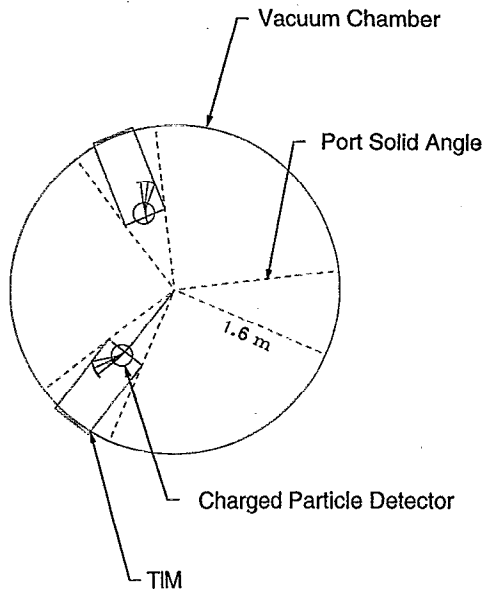
FIG. 1. A schematic of two compact charged-particle spectrometers, as interfaced to the OMEGA-Upgrade facility (taken from Hicks et al.[8,9]). Each spectrometer will measure with high resolution a wide energy spectrum of charged particles. Using a set of photodiodes ($\sim$10) and a 0.8 T permanent magnet, the diagnostic will uniquely determine particle energies and identities from 0.2 MeV up to the maximum charged particle energies (10.6 MeV tritons, 12.5 MeV deuterons and 17.4 MeV protons). With its high-density picture elements, each photodiode has 10^6 single-hit detectors, giving the spectrometer a dynamic range of 1–10^5 particle/shot. For example, in the case of a D–T yield of 10^9 neutrons, about 100 knock-on charged particles will be detected when the spectrometer aperture is 60 cm from the implosion. Furthermore, the measurement of knock-on D and T spectra will allow ρR up to 0.15 g/cm^2 to be measured (for a 1 keV plasma), or 0.3 g/cm^2 if hydrogen doping is used. In addition, the yield and slowing down of secondary protons may be used to determine ρR up to 0.3 g/cm^2. Significantly, this diagnostic will also directly measure the D–D fusion yield and energy degradation of nascent 3 MeV protons. By using two such compact spectrometers to measure the yield and spectra on widely separated ports around the OMEGA-Upgrade target chamber, the implosion and burn symmetry can also be determined.

$x^{t/f}=v_t^2/v_f^2$; m_t (m_f) is test (field) particle mass; $\omega_{pf}=(4\pi n_f e_f^2/m_f)^{1/2}$, the field plasma frequency; $\mu(x^{t/f})=2\int_0^{x^{t/f}}e^{-\xi}\sqrt{\xi}\,d\xi/\sqrt{\pi}$ is the Maxwell integral; $\ln\Lambda_b=\ln(\lambda_D/p_{\min})$, where, for the nondegenerate regime, λ_D is the Debye length and $p_{\min}=\sqrt{p_\perp^2+(\hbar/2m_r u)^2}$; $p_\perp=e_t e_f/m_r u^2$ is the classical impact parameter for 90° scattering, with m_r the reduced mass and u the relative velocity. However, in the low-temperature, high-density regime, electron (not ion) quantum degeneracy effects must be considered in calculating λ_D and $p_{\min}$. Specifically, we semiquantitatively include the effects of strong degeneracy by replacing the electron temperature with an effective temperature, defined as

$$T_{\text{eff}}=\frac{3}{5}\,T_F\left[1+\frac{5\pi^2}{12}\left(\frac{T_e}{T_F}\right)^2-\frac{\pi^4}{16}\left(\frac{T_e}{T_F}\right)^4\cdots\right], \quad (3)$$

where T_F is the Fermi temperature. When this is done, our value for the Coulomb logarithm is in close agreement with the rigorous formulation of the Coulomb logarithm based on

the quantum random-phase approximation of Skupsky.[13] Finally, the effects of collective oscillation have not been included since they become important only for $\gtrsim$14 MeV protons when $T_e\lesssim 1$ keV.[10]

In order to illustrate the results of this analysis, the energetic charged ions of Table I are considered. Figures 2 and 3 show the corresponding Coulomb logarithms for energetic ion(t)–field electron(e) ($\ln\Lambda_b^{t/e}$) and energetic ion(t)–field ion ($\ln\Lambda_b^{t/i}$) interactions. In the case of the energetic ion–electron interaction, Eq. (1) nearly reduces to Trubnikov's result[12] because the mass ratio of field to test particles,
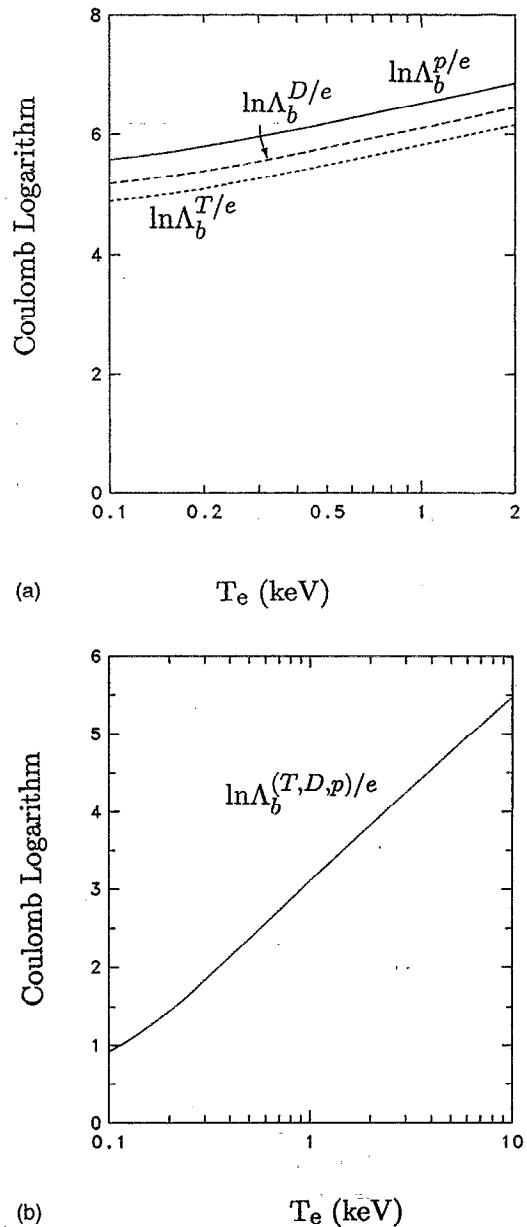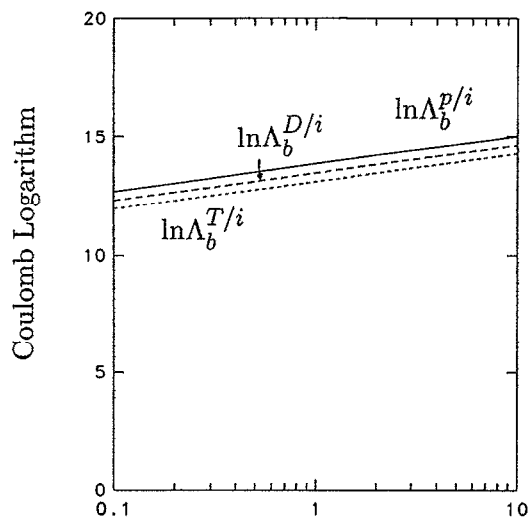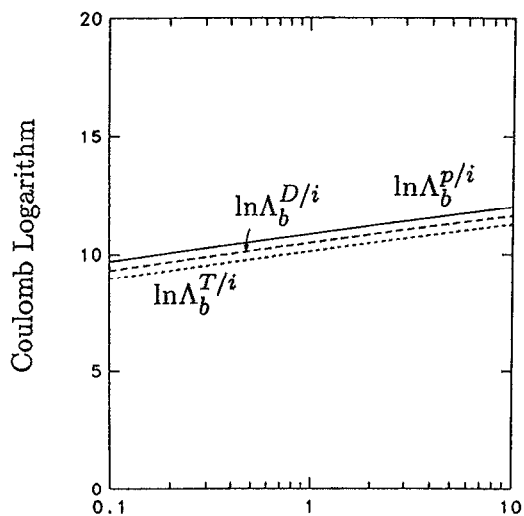

(a)

(b)

FIG. 2. (a) The Coulomb logarithm for 14.1 MeV protons, 12.5 MeV deuterons, and 10.6 MeV tritons interacting with plasma electrons ($n_e=10^{25}$/cm^3). For these calculations, the velocities of the projectile particles are larger than the plasma electron thermal velocity. (b) The Coulomb logarithm for these same, suitably energy degraded, charged particles interacting with plasma electrons when their velocities are smaller than the plasma electron thermal velocity. Stopping power and ρR are calculated only for $T_e\gtrsim 1$ keV, i.e., for $\ln\Lambda_b\gtrsim 2$. (For $\ln\Lambda_b<2$, strongly coupled effects become increasingly an issue.[10,11])

Phys. Plasmas, Vol. 2, No. 6, June 1995

C. Li and R. D. Petrasso   2461

(a) T_i (keV)

ρR (g/cm^2)

FIG. 4. Energy slowing down of 3 MeV, 14.1 MeV, and 17.4 MeV protons as a function of the ρR in a D–T–H (1:1:1 mixture) plasma ($n_e = 10^{23}$/cm^3, $T_e = 5$ keV).

(b) T_i (keV)

FIG. 3. (a) The Coulomb logarithms for 14.1 MeV protons, 12.5 MeV deuterons, and 10.6 MeV tritons interacting with D–T *plasma ions* ($n_e = 10^{25}$/cm^3). (b) The Coulomb logarithms for these charged particles when they have only as little as 5% of their energy remaining.

Figures 4–9 display these results. Note in particular the effects of density upon ρR (Figs. 5 and 6). This is a consequence of two effects. First, since ln $\Lambda_b^{t/e} \sim 5$, the Coulomb logarithm is much more sensitive to the density than if it were 10 or greater. Second, for modest temperatures and high densities, electron degeneracy effects will occur.

Furthermore, the present calculations for 14 MeV protons, 12.5 MeV deuterons, and 10.6 MeV tritons are very similar to the Monte Carlo calculations,[4] where the effects of

m_e/m_t, is of order 10^{-4}. For full energy ions (Table I) interacting with field ions, the Coulomb logarithm (ln $\Lambda_b^{t/i}$) is 12 or larger [Fig. 3(a)]. Even when these ions have only as little as 5% of their initial energy, ln $\Lambda_b^{t/i}$ is still about 10 or greater [Fig. 3(b)]. Thus, virtually through the entire process of energy loss to the plasma, the effects of scattering will always be small.

With this result, Eq. (4) is used to determine the ρR of the energetic particles (Table I) for various conditions of interest,

$$\rho R = \int_0^{E_0} \left(\frac{dE}{\rho \, dx} \right)^{-1} dE. \qquad (4)$$
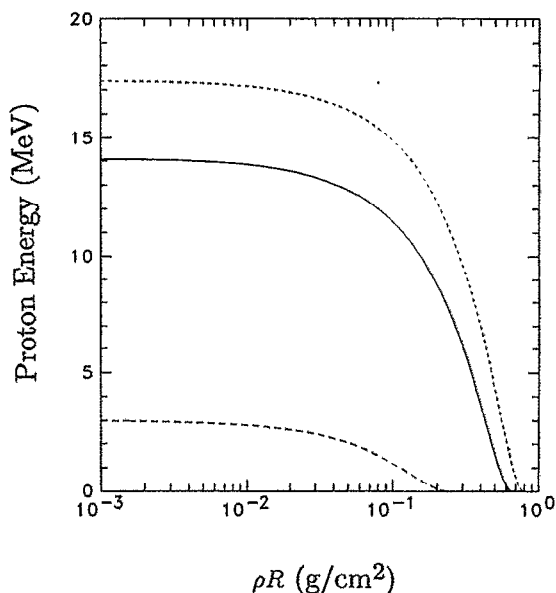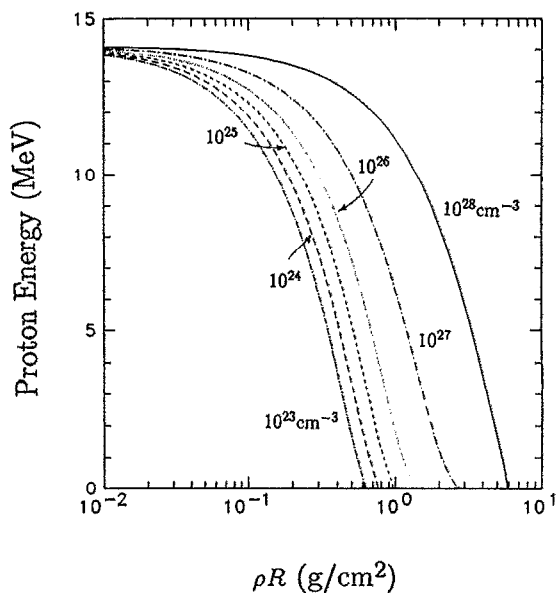

ρR (g/cm^2)

FIG. 5. Energy slowing down of a 14.1 MeV knock-on proton as a function of the ρR in a D–T plasma at $T_e = 5$ keV for various plasma densities. Quantum degeneracy is important for $n_e \gtrsim 10^{27}$/cm^3.
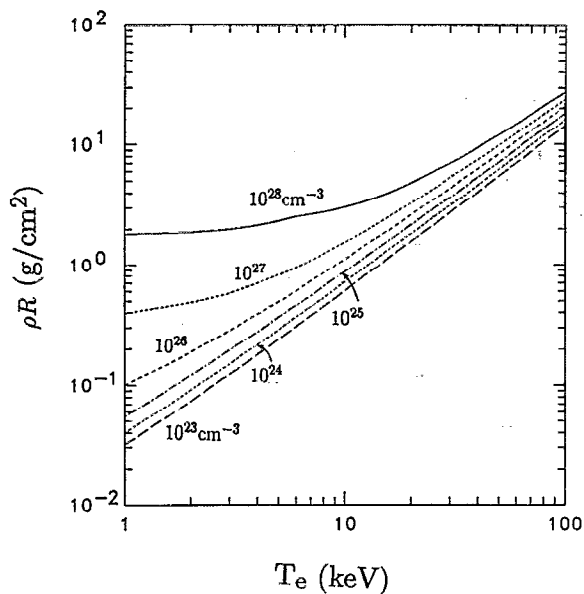
C. Li and R. D. Petrasso

FIG. 6. ρR curves for 3 MeV protons interacting with D–D plasmas of various densities. Quantum degeneracy is important for $n_e \gtrsim 10^{27}/cm^3$ and $T_e \lesssim 5$ keV.
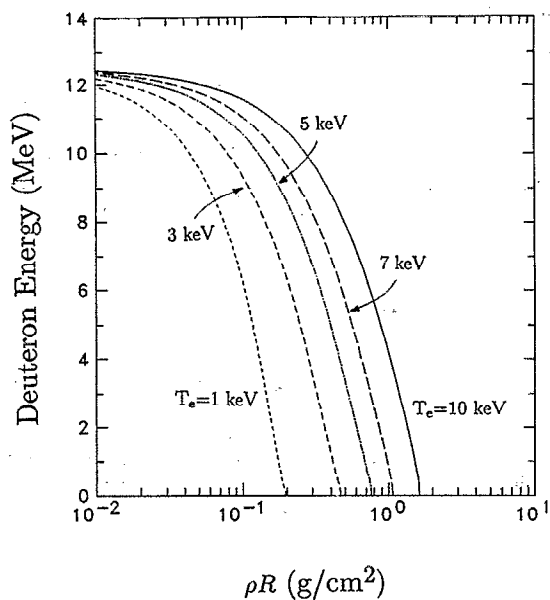

FIG. 8. Energy slowing down of 12.5 MeV knock-on deuterons as a function of the ρR in a D–T–H (1:1:1 mixture) plasma ($\rho = 10$ g/cm^3) for various plasma electron temperatures.

scattering are explicitly included. The similarity of the present results to those of the Monte Carlo approach also indicate that scattering effects are unimportant. In addition, ion stopping becomes increasingly important for the knock-on deuterons and tritons when $T_e \gtrsim 3$ keV (see Figs. 8 and 9).

III. CONCLUSION

In conclusion, we have determined that the effects of scattering are negligible for energetic ions (Table I) appli-

cable to ρR, yield, and/or implosion symmetry diagnostics. These calculations in part determine the potential utility of the proposed charged-particle spectrometer[8,9] that has a wide energy range (0.2–18 MeV), and about 10 million single-hit detectors, each of which can be electronically interrogated.

In the future, the scattering of energetic "test" electrons off field electrons and ions will be treated, a case germane to the fast ignitor concept[14] and to fast electrons generated in stimulated Raman scattering. In such instances, the effects of scattering cannot be ignored.
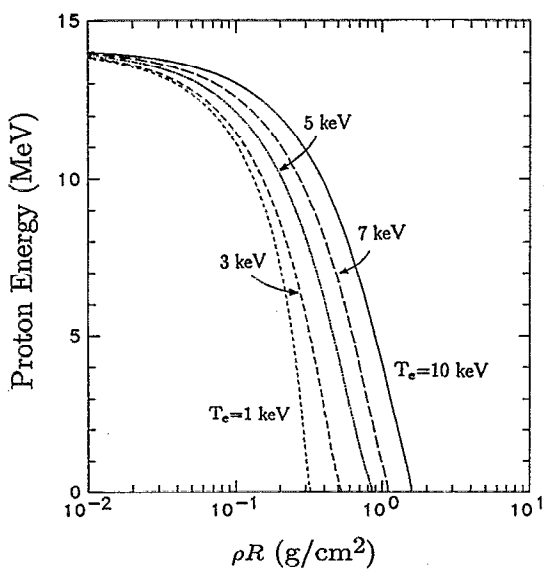

FIG. 7. Energy slowing down of 14.1 MeV knock-on protons as a function of the ρR in a D–T–H (1:1:1 mixture) plasma of $\rho = 10$ g/cm^3 for various plasma electron temperatures. (This density was used in Ref. 4, Fig. 2.[15])
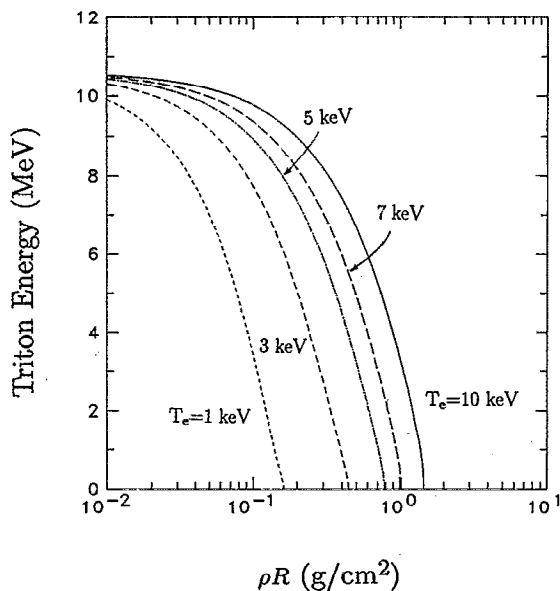

FIG. 9. Energy slowing down of 10.6 MeV knock-on tritons as a function of the ρR in a D–T–H (1:1:1 mixture) plasma ($\rho = 10$ g/cm^3) for various plasma electron temperatures.

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C. Li and R. D. Petrasso