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Review Article

Ion stopping in dense plasmas: A basic physics approach

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Abstract

We survey quite extensively the present research status of ion-stopping in dense plasmas of potential importance for initial confinement fusion (ICF) driven by intense and heavy ion beams, and also for warm dense matter (WDM). First, we put emphasis on every possible mechanism involved in the shaping of the ion projectile effective charge, while losing energy in a target plasma with classical ions and partially degenerate electrons.

Then, we switch to ion stopping by target bound electrons, taking detailed account of mean excitation energies. Free electron stopping has already been given a lot of attention in former works [C. Deutsch et al., *Recent Res. Devel. Plasma* 1 (2000) 1–23; *Open Plasma Phys. J.* 3 (2010) 88–115]. Then, we extend the usual standard stopping model (SSM) framework to nonlinear stopping including a treatment of the Z^3 Barkas effect and a confronting comparison of Bloch and Bohr Coulomb logarithms.

Finally, we document low velocity ion slowing down (LVISD) in single ion plasmas as well as in binary ionic mixtures (BIM), in connection with specific ICF fuels.

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General considerations

Non-relativistic stopping of point like charges in a dense electron fluid has provided us with a fundamentally robust as well as highly versatile paradigm elaborated through a dielectic formulation. So, it thus appears possible to envision now a higher level of complexity in our model approach. The conceptual framework previously developed could also allow for a quantitative treatment of additional basic features of ion-plasma interaction. Those include in-flight balance of the projectile effective charge $Z_{\mathrm{eff}}(V_{\mathrm{p}})$, stopping by electrons bound in the target, or the finite extension (non-punctuality) of the projectile ion electron distribution. The corresponding and suitably extended stopping theory could then be expected to be of quantitative accuracy in modeling the penetration of multi-charged and non-relativistic ions in a small spherical pellet containing a thermonuclear deuterium + tritium (DT) fuel.

Through the remaining electrons bound to the target ions are now directly taking part in the stopping process of the incoming projectile.

These contentions may be given an immediate content by focusing our attention on a high temperature target. Then, the ion projectile-target electron coupling may be considered in the well-known Coulomb logarithm approximation. An obvious extension of the previous standard stopping model (SSM), may thus be written as

$$-\frac{\mathrm{d}E}{\mathrm{d}x}=\frac{4\pi N_0 e^4}{A_{\mathrm{T}} m_{\mathrm{e}} V_{\mathrm{p}}^2}\rho Z_{\mathrm{eff}}^2(V_{\mathrm{p}})(Z_{\mathrm{T}}-\overline{Z})\ln\Lambda_{\mathrm{B}}+ZG(V/V_{\mathrm{e}})\ln\Lambda_{\mathrm{F}} + [\mathrm{ions}], \tag{1}$$

with $G(X)\to 1$ for $V_{\mathrm{p}}\gg V_{\mathrm{the}}$, $G(X)\to 0$ as $(V_{\mathrm{p}}/V_{\mathrm{the}})^3$,

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V_{the} = electron thermal velocity
ρ = target density (g/cm^3)
N_0 = Avogadro number
I = mean excitation energy of target bound electrons

$$\text{with } \Lambda_B = \frac{2m_e V_p^2}{I} \text{ and } \Lambda_F = \frac{2m_e V_p^2}{\hbar\omega_p}. \tag{2}$$

For instance, at $n_e \approx 10^{23}$ cm^{-3} and 100 eV one has $\omega_p \approx 2 \times 10^{16}$/s, $\hbar\omega_p \approx 10$ eV, $\lambda_D \approx 2 \times 10^{-8}$ cm, $n_e\lambda_D^3 \approx 1$.

In Eq. (1), Z_T denotes the target ions atomic number, $\overline{Z}$ their ionicity and A_T, the corresponding atomic mass.

The first term on the right hand side (r.h.s) of Eq. (1) extends straightforwardly to electrons bound to partially ionized ions in plasma target, the usual Bethe expression, valid for an isolated ion. This pinpoints an obvious concern about the adaptability of the mean excitation potential I to plasma surroundings. Even more significant is the novel and conspicuous $Z_{eff}(V)$ behavior in a hot plasma target especially at low Z_T. The enhanced projectile ionization in plasma (EPIP) cannot be extrapolated from the usual trends displayed by cold target homologues. It deserves specific developments considered at first, in the sequel.

The stopping expression (1) has been essentially introduced for illustrating a few specific behaviours of projectile ion stopping in a hot plasma medium. Nonetheless, it retains full validity in a high temperature and weakly coupled plasma target as long as the target ions concept remains operationally meaningfull, i.e. as long as its average extension is smaller than the plasma electron screening length λ_D, i.e.

$$\frac{a_0}{Z_T} \le \frac{743 T_e^{1/2}[\text{eV}]}{n_e^{1/2}[\text{cm}^{-3}]}. \tag{3}$$

When this is not the case, the difference between bound and free target electrons trends become rather blurred. Then, the atomic orbitals are likely to get delocalized around several ions. So, in the weakly coupled regime to which we restrict most of our present attention, the residual and direct ion–ion contribution in the r.h.s of Eq. (1) plays only a minor role (smaller than 5% in most situations of practical interest).

1. Projectile effective charge $Z_{eff}(V_p)$ in a plasma target

We recall the standard Betz expression for the projectile ion effective charge flowing in a neutral and cold gas target, which reads as [4].

$$Z_{eff}(V_p) = Z\left\{1 - 1.034 \times \left[-\left(V_p/2.19 \times 10^8\ [\text{cm/s}]\right)Z^{-0.688}\right]\right\} \tag{4}$$

in terms of the projectile atomic number Z and its instantaneous velocity V_p.

1.1. Hindered recombination

The projectile charge state, in a cold target, gets fixed through a balance between collisional electron losses and bound electron capture of the target atoms. Direct trapping of free electrons is much more problematic to achieve because the excess binding energy has to be evacuated through one of the three processes: (a) radiative recombination, (b) three-body recombination, or (c) dielectronic recombination. Therefore, one should expect different charge states of ions when they pass through plasma or cold targets, except at very high kinetic energy, where bound electron capture is also reduced due to momentum mismatch [5].

In contrast to atomic processes in ordinary plasmas, we emphasize here two specific features: (a) anisotropy of the electron velocity distribution in the ions rest frame, and (b) projectile collisions with target plasma ions are significant.

The dynamical distribution of projectile charge states through target is thus obtained with the coupled equation:

$$\frac{dP_j}{dt} = -P_j\left(\alpha_R^j + \alpha_I^j\right) + P_{j+1}\alpha_R^{j+1} + P_{j-1}\alpha_I^{j-1} \tag{5}$$

where P_j = fraction of projectiles in charge state j, α_R^j, α_I^j = total rate coefficients of recombination and ionization for state charge j.

Given t-dependent outputs rely on charge state, V_p and target parameters. So, the corresponding t-dependent average charge state may be introduced in a standard stopping calculation.

Stopping due to free electrons is derived classically in high temperature plasmas. At each step, energy and velocity data are updated to advance the projectile, up to the following one.

In doing so, temperature effects have been investigated at length (Nardi-Zinamon [6]). Below a 200 eV electron target temperature, ionization of a single electron is the dominant process, mostly for light elements.

Nonetheless, multiple ionization can show up strongly and become the dominant effect especially for heavier projectiles and higher temperatures.

Moreover, kinematic constraints restrict 3-body recombination relative to the radiative one, in particular for highly charged and fast ions. In some cases, a significant dielectronic recombination can outnumber radiative recombination by far.

Finally, the projectile charge state dynamics gets mostly monitored through a balance at equilibrium between collisional ionization and radiative recombination.

At first sight, one seems to recover a statement for coronal equilibrium. However, the restricted electron distribution, in projectile frame, demands that excitation and recombination are performed by same electrons, although with standard Maxwell electrons, excitation arises from the high energy tail of the distribution, while recombination is due to the low velocity part of the bulk.

Typical atomic rates are given on Fig. 1 for ion Cl^{q+} at 1.5 MeV/u.