Influence of charge state evolution in the energy deposition of uranium ions traveling through hydrogen plasma

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1. Introduction

The nuclear fusion is a promising way to obtain clean energy in the future. The inertial confinement fusion driven by heavy ion beams, is one of the method to obtain energy using fusion reactions. For this reason, understanding the physics of heavy ions traveling through plasmas is an important topic in plasma physics. Heavy ions possess good features to heat small samples of matter and, to reach the necessary temperature and density for the nuclear fusion takes place. On the other hand, conventional stripping techniques are limited in their applicability, e.g. short lifetime in foil stripper and lower efficiency in gas stripper. To reach long lifetime and higher efficiency, the use of plasma as a stripping medium has been studied [1]. In stripper devices, one of the most important thing is the prediction of the final charge state distribution of the ion beam and its total energy loss, which the presented work focuses on.

2. Calculation method

According to dielectric formalism, the energy loss of an ion depends on its velocity and on its charge density. Also, it depends on the target through its dielectric function; here the random phase approximation (RPA) model is used because of the excellent results in previous works [2]. The stopping power is defined as the energy loss per unit of length, dE/dx. In this work, we use the electronic stopping power, which shows the energy deposition into the plasma by the projectile, taking into account the transitory charge state of the ion,

$$S_p(t) = \frac{2}{\pi\, v^2} \int_0^\infty dk\, \frac{[Z - \rho_e(k,t)]^2}{k} \int_0^{kv} w\, \mathrm{Im}\left[\frac{-1}{\varepsilon(k,w)}\right] dw, \tag{1}$$

where v and Z are respectively the velocity and nuclear charge of the projectile and $\varepsilon(k,w)$ is the dielectric function of the plasma [2]. Here, we use the Brandt-Kitagawa model (BK) [3] to describe the electronic density distribution of the projectile,

$$\rho_e(k,t) = \frac{\bar{N}(t)}{1 + (k\Lambda)^2}, \tag{2}$$

where $\bar{N}(t)$ is the transitory mean number of bound electrons in the projectile, and Λ is a variational parameter given by,

$$\Lambda(t) = \frac{0.48\,\bar{N}(t)^{2/3}}{Z - \frac{1}{7}\bar{N}(t)}. \tag{3}$$

Finally, the electronic stopping power is given by,

$$S_p = \frac{1}{\tau}\int_0^{\tau} S_p(t)dt, \tag{4}$$

As equation (2) shows, the transitory mean number of bound electrons, $\bar{N}(t)$, must be known. In the present work $\bar{N}(t)$ is calculated by means of two methods.

METHOD 1: SOLVING THE RATE EQUATIONS.

Mean charge state evolution can be calculated by solving the rate equations,

$$\frac{dP_q(t)}{dt} = c_{q+1}P_{q+1}(t) + l_{q-1}P_{q-1}(t) - (c_q + l_q)P_q(t), \tag{5}$$

where c_q, l_q are the total capture and ionization cross sections for a projectile with charge state q, which must be calculated previously [4], and P_q are the fraction of projectiles in the charge state q. Finally, the mean charge state evolution is given by,

$$\bar{Q}(t) = \sum_{q=0}^{Z} qP_q(t), \tag{6}$$

with the normalization $\sum_{q=0}^{Z} P_q = 1$. Then, the transitory number of bound electrons can be calculated as the next equation shows,

$$\bar{N}(t) = Z - \bar{Q}(t). \tag{7}$$

METHOD 2: USING THE EQUILIBRIUM CHARGE STATE.

We can also use the equilibrium charge state of the ion to calculate the transitory number of bound electrons,

$$\bar{N}(t) = N_\infty - (N_\infty - N_0)\,e^{-t/\tau_{ion}}, \tag{8}$$

where N_0 is the initial number of bound electrons, and N_∞ is the number of bound electrons in the equilibrium charge state,

$$N_\infty = Z - \langle Q \rangle\,, \tag{9}$$

where $\langle Q \rangle$ is the equilibrium charge state. In the equation (8), τ_{ion}, is the ionization time,

$$\tau_{ion} = \frac{1}{n_e v \sigma}, \tag{10}$$

where n_e is the free electron density of the plasma, v is the projectile velocity and σ is the ionization cross section.

This method requires knowing previously the equilibrium charge state as equation (8) shows. The more complete method makes use of rate equations. In the equilibrium, the fractions of projectiles, A_q, are constants, such that, we can obtain the equilibrium charge state supposing that the stationary case in equation (5) is reached,

$$\frac{dP_q(t)}{dt} = 0 \rightarrow l_q P_q - c_{q+1} P_{q+1} = 0. \tag{11}$$

Then we have to solve a ordinary equation system to calculate the P_q, and the equilibrium charge state is given by,

$$\langle Q \rangle = \sum_{q=0}^{Z} q P_q \tag{12}$$

However, in the present work, we use the simple formula of Northcliffe with the Kreussler *et al.* stripping criterion [5] adapted to plasma conditions to calculate the charge state equilibrium,

$$\langle Q \rangle = Z \left[1 - e^{-\frac{v_r}{Z^{2/3} v_0}} \right], \tag{13}$$

where v_0 is the Bohr velocity and v_r is the relative velocity,

$$v_r = \frac{v_e^2}{6v} \left[\left(\frac{v}{v_e} + 1 \right)^3 - \left| \frac{v}{v_e} - 1 \right|^3 \right]; \quad v_e = \left(\frac{3}{5} v_F^2 + 3 V_{the}^2 \right)^{1/2}, \tag{14}$$

where v_F and v_{the} are respectively the Fermi velocity and thermal velocity of plasma electrons.

3. Results

Figure 1 shows the mean charge state evolution of an uranium ion beam traveling through fully ionized hydrogen plasma as a function of the initial charge state of the projectile. The smaller charge state of the method using the equilibrium charge state (orange lines) is because of the slight difference in the equilibrium charge state between Kreussler *et al.* model (28.35+) and rate equations (33.6+).

Figure 2 shows the energy loss of the uranium ion beam colliding with hydrogen gas and plasma. The experimental data have been obtained from [6]. It can see that our theoretical calculations agree very good with the experimental data.

4. Conclusions

In this work, it has been established two models to calculate the charge state evolution of heavy ions colliding with fully ionized plasma. Furthermore, the initial charge state has been included in the energy loss calculation, concluding that it is very relevant in order to to reproduce the experimental data (Figure 2, left). Finally, it has been demonstrated the necessity of using the Brand-Kitagawa charge state distribution in the energy loss calculation (Figure 2, right).

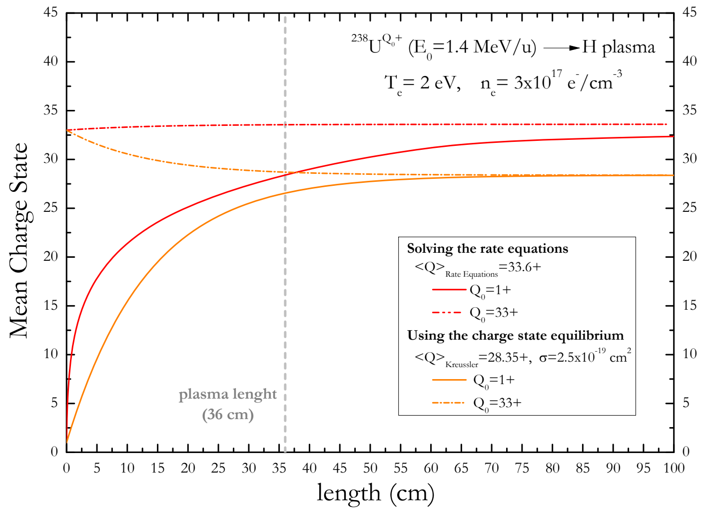

Figure 1: Mean Charge State Evolution

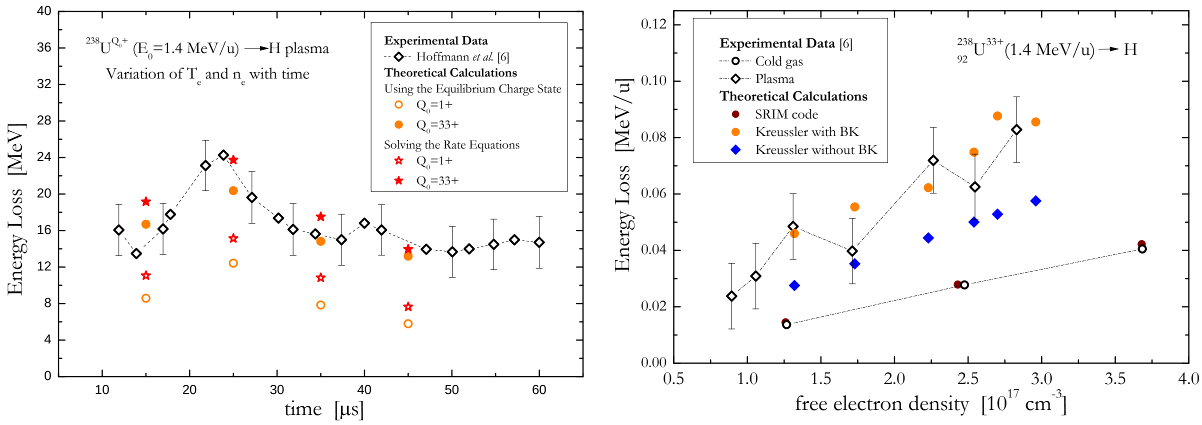

Figure 2: Energy loss as a function of plasma conditions

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