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INTERACTION OF HEAVY IONS BEAMS WITH GAS AND PLASMA TARGETS

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Résumé - Nous discutons des différentes informations que l'on peut obtenir à partir des expériences d'interaction entre des faisceaux d'ions lourds et des cibles gazeuses ou ionisées ayant une densité comprise entre $10^{17}$ et $10^{18}$ e.cm$^{-3}$. Deux points particuliers sont évoqués : Les termes correctifs au comportement dominant du pouvoir d'arrêt et l'influence de la dynamique sur l'évolution de l'état de charge du faisceau.

Abstract - We discuss in this paper some theoretical informations that one can get from experimental results of heavy ions beams-target interaction in the case of gas and plasma with electronic density ranging between $10^{17}$ and $10^{18}$ e.cm$^{-3}$. We focus on two particular points: Corrections to the dominant behavior of stopping power and dynamical influence on beam charge state.

I. INTRODUCTION

In connection with Heavy Ions beams inertial Fusion (HIF) (1), first experiments on energy loss of fast heavy ions in dense plasma have begun in France and Germany (2,3). Plasmas encountered have electronic density ranging from $10^{17}$ to $10^{18}$ e.cm$^{-3}$ and density of $10^{19}$ e.cm$^{-3}$ is expected in a near future. The effective length $L_p$ (product of the electron density $n_e$ by the plasma length $l_p$) in these discharges ranges from $3 \times 10^{16}$ to $10^{20}$ e.cm$^{-2}$. The beams kinetic energy is one or two MeV/u. We want to discuss here about the fundamental theoretical stopping power parameters that can be tested in these experiments.

The most obvious plasma effect is an enhanced stopping of nearly twice the cold gas one. Beside that there are other differences between gas and plasma which are important in the case of heavy ions beams (atomic number greater than ten). We shall speak here first of the correction to the dominant behavior of the stopping power and then about the evolution of the projectiles mean ionization state.

II. STOPPING POWER

Take a beam of atomic mass $M$, atomic number $Z$, initial velocity and kinetic energy $V_0$ and $E_0$ flowing through a target along the $x$ axis. It has at some distance $x$ from the front of the plasma (or gas) a kinetic energy $E(x)$, a

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velocity \( V(x) \) and a mean ionization state \( Z^*(x) \). Variation of \( E(x) \) with \( x \) can be written as (atomic units are used throughout):

\[
\frac{dE(x)}{dx} = -S(V(x),Z^*(x)),
\]

with the stopping power \( S \):

\[
S(V,Z^*) = \frac{4\pi Z^* Z_p}{v^2} n_p L(V,Z^*),
\]

the stopping number \( L \) can be put in the form

\[
L(V,Z^*) = \frac{Z^*}{Z_p} L^f v^2 + \frac{Z_p - Z^*}{Z_p} L^o + \frac{Z^*}{v} L_1 + \frac{Z^* Z_p}{v^2} F(V^2) + \frac{Z_p n_p}{m_p} L_1,
\]

(1)

where \( Z_p, m_p, Z^*_p \) and \( n_p \) are respectively atomic number, mass, ionization and particle density of the plasma ions, \( L^f \) and \( F^o \) are Born I stopping number on free and bound electrons and are the so called dominant terms, \( L_1 \) and \( F(V^2) \) are corrections to \( L \) coming from distant and close collisions, \( L_1 \) gives the elastic scattering contribution of the plasma ions and is negligible here.

We focus now to the experiments /2,3/ that is a 35 cm long hydrogen discharge and look only at the two limit cases: cold gas and fully ionized plasma having the same total number of electrons. Then the two stopping power can read as:

\[
in the gas case:
S_g(V,Z^*_g) = \frac{4\pi n_p}{v^2} Z^*_g L^g(V,Z^*_g),
\]

(2)

with \( L^g(V,Z^*_g) = L^o + \frac{Z^*_g}{v} + L_{1g} + \frac{Z^*_g Z_p}{v^2} F_g(V^2) \)

\[
\]

and in the plasma case:
\[
S_f(V,Z^*_f) = \frac{4\pi n_p}{v^2} Z^*_f L^f(V,Z^*_f),
\]

(3)

with \( L^f(V,Z^*_f) = L^o + \frac{Z^*_f}{v} + L_{1f} + \frac{Z^*_f Z_p}{v^2} F_f(V^2) \)

Then four quantities can be different in the two cases they are, \( Z^*, L^o, L_1 \) and \( F(V^2) \). First of all let us make sure that we are in good situation to look at the interaction between our beams and plasma. We have an electronic density ranging from 1 to \( 10^{17} \) e.cm\(^{-3} \) while the temperature is one or two eV. With a beam of 1.4 MeV/u the incident velocity \( V \) equals 7.5 and therefore is much larger than the mean electron velocity either in gas or in the plasma, so only the high velocity limits of (2) and (3) can be tested.

In this high velocity regime, the dominant term \( L^o \) reduces to the well known Bethe result:

\[
L^o = Log \frac{2V^2}{I} \quad \text{and} \quad L^f = Log \frac{2V^2}{\omega_p}.
\]

Hydrogen mean excitation energy \( \omega_p = 1 / \sqrt{3}, /4/ \) and at \( n_e = 2.10^{17} \) cm\(^{-3} \), the plasma frequency \( \omega_p \) equal \( 6.1 \) \( 10^{-4} \)

that yields \( L^f = 12.13 \) and \( L^o = 5.25 \) with a ratio of 2.3 which is indeed a very strong plasma effect.

Next we have to see if the effective length \( L_p \) allows a sufficient loss
\[ \Delta E = E(0) - E(1_p). \] Supposing \( \Delta E / E(0) \ll 1 \) (3) can be written as:

\[
\frac{\Delta E}{E} = -2.4 \times 10^{-22} \left( L_p \text{cm}^{-2} \right) \frac{Z^*}{M} \frac{L^f}{e^2 \text{(MeV/u)}},
\]

with \( e = E / M \). Results for \( \Delta E / E(0) \) are reported in Table I taking \( L^f = 10 \), \( L_p = 3.5 \times 10^{18} \text{cm}^{-2} \) and \( e = 1.4 \text{MeV/u} \).

Table I. \( \Delta E / E(0) \) from Eq. (4) for different characteristic ions.

<table>
<thead>
<tr>
<th>incident ions</th>
<th>U</th>
<th>S</th>
<th>C</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z^*(0) )</td>
<td>33</td>
<td>11</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>( \Delta E / E )</td>
<td>0.23</td>
<td>0.18</td>
<td>0.13</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Therefore the interaction is big enough to allow good precision for all incident ions except that the energy loss of protons at a density of \( 10^{17} \text{cm}^{-3} \) could be difficult to measure.

Let us look now at the two corrections \( L_1 \) and \( F(V^2) \). As can be seen from Eq. (2) and (3), the stopping number is written as a series expansion of the Born parameter \( b = Z^* / V \). At 1.4 MeV/u \( b \) ranges from 0.13 for H to 4.4 in the case of uranium beam. Then comparison of stopping in gas and plasmas for light and heavy particles can give informations on \( L_1 \) and \( F(V^2) \). The fact that these corrections are important has been already tested in the cold gas case as shown in Ref. 4 where experimental stoppings of heavy ions with \( E = 1.4 \text{MeV/u} \) flowing through cold Argon gas are compared to theoretical predictions. For Uranium beam, data are 25% lower than the dominant stopping. Each of the corrections term is nearly as large as the dominant term but, because they are of opposite sign (\( L_1 \) is always positive and \( F(V^2) \) negative) the sum of them nearly cancels. Due to this last fact it is quite difficult to have some precise information from experimental data with cold target for only one of these corrections.

To see how stopping in plasma can help us let us examine in more details \( L_1 \) and \( F(V^2) \).

\( F(V^2) \) comes from close collisions /5,6/ and then one supposes that target electrons act as if they were free, taking only into account their velocity distribution and the minimum energy transferred in one collision. In the high velocity regime \( F(V^2) \) reduces to:

\[
F(V^2) = - \sum_{k=1}^{\infty} \frac{1}{k} \frac{b^2}{k^2 + b^2}, \quad b = \frac{Z^*}{V},
\]

it is then the same expression for a free or a bound electron : \( F_f(V^2) = F_b(V^2) = F(V^2). \) On the opposite side \( L_1 \) comes from distant collision, it is calculated using a second order perturbation theory /7/. The important fact for \( L_1 \) is that, at high velocity, it increases with the electron binding energy and is therefore negligible for free electrons. Finally \( L \) and \( L^f \) reduce to:
One can therefore obtain $F(v')$ from (5.b), put it into (5.a) and get $L_1$. To see this in a more quantitative way we have reported in Table 2 results for $Z^* = 33, 13, 6$ and $1$ with $E = 1.4$MeV and $n_e = 2.10^{17}$e.cm$^{-3}$ where we have $L_0^f = 12.13$ and $L_0^B = 5.25$.

TABLE 2 : Relative importance of the different parameters of Eq. 5, with $C=-Z^*F(v')/vZ$ and $d = Z^*L_1/v^2$

<table>
<thead>
<tr>
<th>$Z^*$</th>
<th>$L_0^f$</th>
<th>$L_0^B$</th>
<th>$L_0^f/L_0^B$</th>
<th>$C/L_0^f$</th>
<th>$C/L_0^B$</th>
<th>$D/L_0^f$</th>
<th>$L_0^f/L_0^B$</th>
<th>$L_0^B/L_0^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>3.84</td>
<td>10.1</td>
<td>2.63</td>
<td>0.20</td>
<td>0.53</td>
<td>0.17</td>
<td>0.73</td>
<td>0.83</td>
</tr>
<tr>
<td>13</td>
<td>4.38</td>
<td>11.1</td>
<td>2.51</td>
<td>0.10</td>
<td>0.26</td>
<td>0.06</td>
<td>0.83</td>
<td>0.91</td>
</tr>
<tr>
<td>6</td>
<td>4.88</td>
<td>11.6</td>
<td>2.38</td>
<td>0.04</td>
<td>0.10</td>
<td>0.02</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td>1</td>
<td>5.23</td>
<td>12.1</td>
<td>2.32</td>
<td>0.002</td>
<td>4.0E-3</td>
<td>4.0E-3</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

One therefore can see that $L_0^f$ and $L_0^B$ are correctly given from H beam while $F(v^2)$ account for 20% of the $Z^*=33$ plasma stopping, and $L_1$ for 17% of the cold gas result at the same projectile ionization.

In conclusion to this part, we can state that non linear effects in stopping are important in the experiments /2,3/ and comparison of stopping in gas and plasma allow to test each of the two correction terms (close and distant contribution) with good precision.

II. Ionization state

At first it is important to precise two quantities connected with, but distinct from, $Z^*$.

Take a light ions beam of atomic number $z$ which is supposed fully ionized. Its stopping power is $S(V,z)$. Take an other ions beam of large atomic number $Z$ with a stopping power $S(Z^*,V)$, we can define its effective charge $Z_{ef}$ by : $S(V,Z^*) = Z_{ef}^2 S(V,z) \text{ or } Z_{ef}^2 = \frac{S(V,Z^*)}{S(V,z)} z^2$. $Z_{ef}$ is then a useful parameter to express stopping of heavy projectiles in term of experimental light ion stopping (most often proton or alpha particles). In view of (1) the connection between $Z_{ef}$ and $Z^*$ comes from :
\[ Z_{ef} = \frac{Z^* L(V,Z^*)}{L(V,z)} \]  

The ratio \( Z_{ef}/Z^* \) is then the square root of the two last columns in Table 2. One has to take care that most experimental tables or parametrisation give \( Z_{ef} \) and not \( Z^* /8/ \).

A more theoretical quantity is the equilibrium charge \( Z_{eq}(V) \):

\[ Z_{eq} = \lim_{L_p \to \infty} Z^*(Z,V) \]  

\( Z_{eq} \) can also be defined as the mean ionization state where the rate coefficient for electron loss is equal to the rate coefficient for electron gain by the beam.

To examine the evolution of \( Z^* \) during the slowing down process we use a simple model well adapted for dense plasma which is the average atom model using hydrogenic levels with screening constants /9,10/. Taking this mean atom with ten energy levels of principal quantum number \( n \) populated by \( P_n \) electrons we can write:

\[ Z^* = Z - \sum_{n=1,10} P_n, \]  

and then \( \frac{dz^*}{dt} = - \sum_{n=1,10} P_n \), with

\[ \dot{P}_n = -P_n (1(n,n) + \sum_{k \neq n} (2k^2 - P_k) l(n,k)) \]

\[ + (2n^2 - P_n) (g(n,n) + \sum_{k \neq n} P_k g(k,n)) \]

where, when \( k \neq n \) \( l(n,k) = g(n,k) \) represents the rate coefficient for one electron transfer from the level \( n \) to the level \( k \) supposing that there is one electron in level \( n \) and one free place in level \( k \), \( g(n,n) \) and \( l(n,n) \) denote rate coefficients for recombination and ionization. \( l \) and \( g \) are calculated owing to electron and ion ionization and excitation, spontaneous decay, bound-bound and radiative recombination. Equation 7 has to be slightly modified to treat dielectronic recombination and autoionization process. Details for the rates coefficients are reported elsewhere/6/.

An example of the contributions coming from different atomic collisions is displayed in Fig. 1 for Krypton beam with 1.4MeV/u flowing through hydrogen at a density of 1.8 \( 10^{18} \) e.cm\(^{-3} \) and a temperature of 1.6eV which gives an ionization of nearly one half. At a given charge the ionization state changes due to the largest rate coefficient. We can see in Fig. 1 that at equilibrium this rate is minimum and we call it \( \tau_{eq} \). Therefore the characteristic time to reach equilibrium is given by \( t_{eq} = 1/\tau_{eq} \).

In dealing with the interaction of a beam with a discharge one can define the interaction time \( t_i \) :

If \( \Delta E / E \ll 1 \) \( t_i \) is equal to \( 1_p / \bar{V} \), with \( \bar{V} \) the mean velocity. In the opposite limit \( t_i \) is given by the stopping time : \( t_i \propto \frac{2. E(0)}{S(z^*(0),V(0)), V(0)} \)

One can have the two limit cases :

* \( t_{eq} \ll t_i \) in that case \( z^* \propto Z_{eq} \)

* \( t_{eq} \gg t_i \) projectiles have not the time to reach equilibrium either because the plasma is too short or because they are stopped before.

To look at the two limits we compare hydrogen plasma at the density of 1.6 \( 10^{18} \) e.cm\(^{-3} \) at temperatures of 1.6eV and 3.0eV, in the last case the ionization is 0.99. With these two temperatures, the ionization rates remain nearly constant, the free electrons rates increase by a factor of two and the
bound-bound rate coefficient is divided by 50. One can see in Fig. 1 that in the low temperature case \( t_{eq} \approx 2\text{ns} \) while with high temperature \( t_{eq} \approx 100\text{ns} \).

\[ T_e = 1.6 \text{ eV} \]

Fig. 1- Rates coefficient for different atomic collision on Kr having a constant kinetic energy of 1.4 MeV and flowing through hydrogen with \( n_e = 1.6 \times 10^{17}\text{cm}^{-3} \).

The beam energy and velocity evolution are displayed on Fig. 2a,b for the two regimes with the same projectiles as in Fig. 1. We have to notice that, because we are in low density plasma, projectiles excitation is not important here, so for atomic processes, only the effective length is relevant. The only modification with density comes from the plasma frequency in the free electron stopping power, but because we are at high velocity it has a small influence so one can say, for instance, that the state of projectile after 30 cm of a plasma with a density of \( 1.6 \times 10^{17}\text{e.cm}^{-3} \) can be read at 3 cm on Fig. 2a,b and then these figures cover all the range in the effective length up to \( 10^{20}\text{e.cm}^{-2} \).

When looking at Fig. 2a one can see that the interaction time remain always smaller than the stopping time and that it reaches the equilibrium time for an effective length of \( 2.4 \times 10^{18}\text{e.cm}^{-3} \). This can also be seen on Fig 3a where the rate coefficients during the slowing down of the projectiles are displayed. The rate for electron gain equal the electron loss one for ionization below 20. When we increase the temperature from 1.6 to 3 eV, the evolution of the ionization and of the kinetic energy are greatly modified as can be seen from Fig. 2b. The stopping is increase so that the interaction time can equal the stopping time and is always smaller than the equilibrium one. This last fact is clearly shown on Fig. 3b: the electron loss rate never stay close to electron gain one. An other important point is that high initial charge states remain unchanged during the most part of the slowing down process and this can, in particular, increase the straggling when there is a broad ionization charge state distribution.

In term of the importance in the different atomic process one can notice first that, although the plasma ionization is 0.99, the most effective recombination rate comes from bound-bound process which becomes negligible only at higher temperature. The second important point is that dielectronic recombination is a resonant reaction as can be seen in Fig. 3b and then in
\( T_e = 1.6 \text{ eV} \)

\( T_e = 3.0 \text{ eV} \)

Fig. 2- Evolution of the ionization (left scale) and of the kinetic energy (right scale) for the same incident ion and plasma as in Fig. 1. a) Plasma temperature is 1.6 eV, b) Plasma temperature of 3 eV
Fig. 3 - Rate coefficients for different atomic collisions during the slowing down of the projectile. Same incident ion and plasma as in Fig. 1. a) Plasma temperature of 1.6 eV, initial charge state = 34. b) Plasma temperature of 3. eV, initial charge state = 18
some particular case can play a more important role /11/. Finally one can say, for stopping in highly ionized plasma, that the stopping power acts as a cut-off for small rate coefficient. Defining a rate $\tau_z = 1 / \tau_z$, one can state that processes with a rate smaller than $\tau_z$ have not the time to play a significant role and then can be neglected.

In conclusion to this part, we can state that the most important parameter to evaluated stopping and charge state of heavy beam is the ionization of the plasma which changes mainly the recombination rate coefficient. In a highly ionized plasma the slowing down must be analysed as a transient phenomenon using a fully dynamical description.

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