Low velocity ion stopping of relevance to the US beam-target program

CLAUDE DEUTSCH AND ROMAIN POPOFF

LPGP (CNRS-UMR 8578), Université Paris-Sud, Orsay France

(RECEIVED 20 March 2006; ACCEPTED 31 May 2006)

Abstract

We have focused our attention on the stopping mechanisms involved in the recently proposed ion beam-target US program. This mechanism emphasizes out production of warm dense matter through pulsed ion beams, linearly accelerated, and interacting with thin foils in Bragg peak conditions. We reviewed the relevant energy loss mechanisms involved at moderate and low velocity ion projectile. Small velocities close to zero are given some attention.

Keywords: Bragg peak; Heavy Ion Fusion; Low velocity ion stopping; US program

1. INTRODUCTION

The recently reoriented US heavy ion program (Logan *et al.*, 2005) advocates the production of warm dense matter (WDM) with intense ion beams partially stopped in thin foil, in the vicinity of the Bragg peak (Grisham, 2004). The idea is to warm up as uniformly as possible target foils exposed to intense heavy ion beams that have been linearly accelerated. More precisely, it is planned to use moderate energy ions (~0.3–3 MeV/a.m.u) as low cost drivers for high energy density physics (HEDP) experiments. Target thickness could then be selected, so the ion beam enters and then leaves the target in close vicinity of the dE/dx peak, so that $d^2E/dx^2 \cong 0$. As a result, high uniformity of energy deposition can be expected with a maximum of energy per beam particle deposited in target (Grisham, 2004).

The formal presentation of this program (Logan *et al.*, 2005) details high-current ion sources injection, transport, final focussing, chambers and targets for HEDP, and inertial fusion energy (IFE), driven by the induction of linac accelerators. In order to optimize WDM production, this program addressed the physics of neutralized beam compression and focusing to the high intensities requested for efficient target heating (Ng *et al.*, 2005).

Despite several very recent and thorough presentations, this conspicuous program does not pay much attention to the energy loss mechanisms actually at stake in the interaction processes underlying WDM production. It is for this reason that we intend to review and formalize to a certain extent, the basic physics of intermediate and low velocity ion stopping. As well documented (Deutsch, 1986; Deutsch *et al.*, 1989; Hoffmann *et al.*, 1990; Deutsch & Maynard, 2000), the given stopping power is no longer $\sim V_p^{-2}$, with V_p denoting the ion projectile velocity, but rather $\sim V_p$, where $V_b \ll V_{the}$ is the target electron thermal velocity. We intend to emphasize that the Bragg peak should be treated as an intermediate (or low $V_b \sim V_{the}$) or low V_p energy loss. Fortunately, the US proposal is concomitant with many theoretical and numeral studies devoted to low V_p stopping, mostly in cold matter. Therefore, we review the given proposed results in connection with the US program.

Section 2 revisits the intermediate and low velocity (ILV) regime when target electrons stop ion beams with $V_b < V_{the}$ while V_p remains significantly larger than V_{thi} thermal ion velocity in target. Such a situation is already well documented through thermonuclear alpha heating of fusion plasmas (Goldston & Rutherford, 1995).

In Section 3, we stress the operational significance of ion energy loss near $V_p = 0$, and for an arbitrary coupling between projectile charge Z_p and target electrons, in a weakly coupled target plasma with $\Gamma_e = e^2/k_B Ta < 1$ and $a = (4/3\pi n_e)^{-1/3}$ with Z = target ion charge, n_e denoting the target electron number density. It should also be appreciated that a few eV electron fluids can remain mostly non-degenerate with $\Gamma_e \sim 1$.

Section 4 highlights the progress of a highly charged and low velocity ion beam through dense plasma before recombination with conveyed target electrons takes place. Prospective remarks are presented in Section 5.

Address correspondence and reprint requests to: Claude Deutsch, LPGP (CNRS-UMR 8578), Université Paris-Sud, Orsay, France. E-mail: claude.deutsch@pgp.u-psud.fr

2. ILV ION STOPPING IN ELECTRON-ION TARGET PLASMA

Now, we detail the above advocated ILV regime. First, we make the proviso that intra-beam ion-ion correlations can be safely neglected in dense plasma targets. Otherwise stated, the given mean ion distance is likely to remain orders of magnitude above target electron screening length (Debye at $T_e \gg T_F$, or Thomas-Fermi $\lesssim T_F$). This assumption is very close to the "dilute beam in target" assumption, commonly used for heavy ion beam (HIB) driven IFE (Deutsch, 1986).

The basic interaction scheme underlying the recently proposed US program (Grisham, 2004; Logan *et al.*, 2005) is vividly pictured on Figure 1.

It is also implied that under intense ion beams irradiation, thin target foil will be very rapidly heated to a hot plasma state. In such a situation, ILV mechanisms underlying Bragg peak energy loss are expected to rely on a $V_b < V_{the}$ and $V_b > V_{thi}$ regime. In a $\Gamma < 1$, target plasmas, stopping quantities are likely to be linearly dependent on the electron Coulomb logarithm $\ell n\Lambda$, with

$$\Lambda = 9n_D = \frac{1.548 \times 10^{10} T_e^{3/2}\ (\text{eV})}{n_e^{1/2}\ (\text{cm}^{-3})}, \tag{1}$$

where n_D denotes the number of electrons in a Debye sphere, with $T_e = T_i$ in the target.

Then ion stopping at moderate velocities with $V_{thi} \ll V_b \ll V_{the}$ in a target plasma assumed to be composed of Maxwellian ions and electrons, for ion beam (M_b, Z_b, E_b) and target ions (M, Z) can be expressed (Goldston & Rutherford, 1995) for $V_b \ll V_{the}$ as

$$\frac{dE_b}{dt} = -\frac{2^{1/2} n_e Z_b^2 e^4 m^{1/2} \ell n\Lambda}{6\pi^{3/2}\varepsilon_0^2 M_b T_e^{3/2}}\, E_b, \tag{2}$$

m = electron mass, and

$$\frac{dE_b}{dt} = -\frac{2^{1/2} n_i Z^2 Z_b^2 e^4 M_b^{1/2} \ell n\Lambda}{8\pi\varepsilon_0^2 M E_b^{1/2}}, \tag{3}$$

for $V_b \gg V_{thi}$. Altogether one gets

$$\frac{dE_b}{dt} = -\frac{2^{1/2} n_e Z_b^2 e^4 m^{1/2} \ell n\Lambda}{6\pi^{3/2}\varepsilon_0^2 M_b}\left(\frac{E_b}{T_e^{3/2}} + \frac{C}{E_b^{1/2}}\right), \tag{4}$$

where

$$C = \frac{3\pi^{1/2} Z M_b^{3/2}}{4 m^{1/2} M} \cong 1.19 Z M_b^{3/2}, \tag{5}$$

for M_b arbitrary and $M \cong 48$ (titanium), in m unit. Critical $E_{b,crit}$ fulfilling

$$\frac{E_{b,crit}}{T_e} = C^{2/3} = 1.12 Z^{2/3} M_b, \tag{6}$$
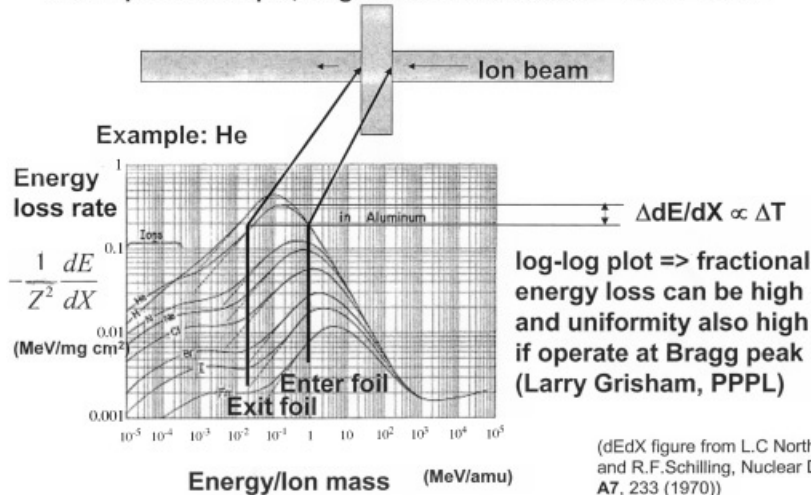
denotes a crossover between a situation mostly controlled by electron stopping $(E_b > E_{b,crit})$ while $(E_b < E_{b,crit})$ pertains to stopping mostly arising from target ions.

Let us recall that $dE/dx = V_b^{-1} \times dE/dt$, and that in context of producing WDM with Ti (titanium) targets, one should expect $Z = 1, 2$ (1 or 2 eV target temperature). WDM with quasi-classical electrons may be obtained from C_s targets at a few eV, in view of its very Fermi temperature $T_F \sim 1.7$ eV and $C = 0.43\, Z M_b^{2/3}$.

Neglecting multiple scattering effects on target ions, one can ignore velocity diffusion coefficient compared to dynamical friction featured as ion beam losses on target electron and ion. This amounts to a Fokker-Planck description,

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or "foam" metal

Ion beam

Example: He

Energy loss rate

$-\dfrac{1}{Z^2}\dfrac{dE}{dX}$

(MeV/mg cm^2)

in Aluminum

$\Delta dE/dX \propto \Delta T$

log-log plot => fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

Enter foil
Exit foil

Energy/Ion mass   (MeV/amu)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

Fig. 1. Warm dense matter (WDM) production at Bragg peak (Logan *et al.*, 2005).

$$\frac{\partial f_b}{dt} = \frac{n_e Z Z_b^2 e^4 \ell n \Lambda}{4\pi\varepsilon_0^2 M_b M} \frac{\partial}{\partial \vec{V}_b}\left[\frac{\vec{V}_b}{V_b^3}\left(1 + \frac{V_b^3}{V_{b,crit}^3}\right) f_b \right], \qquad (7)$$

where

$$V_{b,crit} = \left(\frac{2E_{b,crit}}{M_b}\right)^{1/2} = 3^{1/3} Z^{1/3}\left(\frac{\pi}{2}\right)^{1/6}\left[\frac{T_e}{m^{1/3}M^{2/3}}\right]^{1/2} \qquad (8)$$

for the ion beam distribution, with a critical velocity $V_{b,crit}$ M_b-independent. Again for a T_i target ($M = 48$), Eq. (8) specifies to

$$V_{b,crit}\,(\text{cm/sec}) = 1.47 \times 10^6 \times Z^{1/3} T_e^{1/2}\,(\text{eV}).$$

3. ZERO VELOCITY ION STOPPING

Concentrating now on the most significant ion stopping arising from target electrons, we pay attention to

$$S(V_b) \equiv \frac{dE_b}{dx}(V_b), \qquad (9)$$

near $V_b = 0$. The ratio $S(V_b)/V_b$ usually monitors a linear stopping profile, up to 100 keV/a.m.u (Paul & Schinner, 2003) in cold matter. Similar trends are also reported in highly ionized plasma (Deutsch, 1986; Deutsch & Maynard, 2000).

From now on, we intend to make use of a very powerful connection between very low velocity ion stopping and particle diffusion (Dufty *et al.*, 2004; Talin *et al.*, 2003; Forster, 1975) through Einstein characterization of ion mobility associated to thermal electron fluctuations in target, around the slow ion projectile visualized as an impurity immersed in a dense and homogeneous electron fluid. The given relationship thus reads as

$$\lim_{V_b \to 0} \frac{S(V_b)}{V_b} = \mu^{-1} = k_B T_e D^{-1} = \frac{Z_b^2 e^2}{M_b}\int_{-\infty}^{\infty} dt\langle \vec{E}_e(t)\cdot\vec{E}_e\rangle, \quad (10)$$

in terms of a Green-Kuho integrand (Forster, 1975) involving electric field fluctuations from the target electrons. $\vec{E}_e(t)$ qualifies as the total electric field at impurity due to surrounding electrons.

A fundamental restriction on the relations (10) arises from the strong inequality $M_p/m \gg 1$, between projectile and electron mass. The integrand on the right-hand side in Eq. (10) is illustrated on Figure 2, which contrasts molecular-dynamics (MD) simulations to an analytic model using a short range regularized Coulomb effective interaction between "impurity" Z_b and target electrons (Deutsch, 1977), given as

$$V(r) = -\frac{Z_b e^2}{r}\,(1 - e^{-r/\delta}), \qquad (11)$$
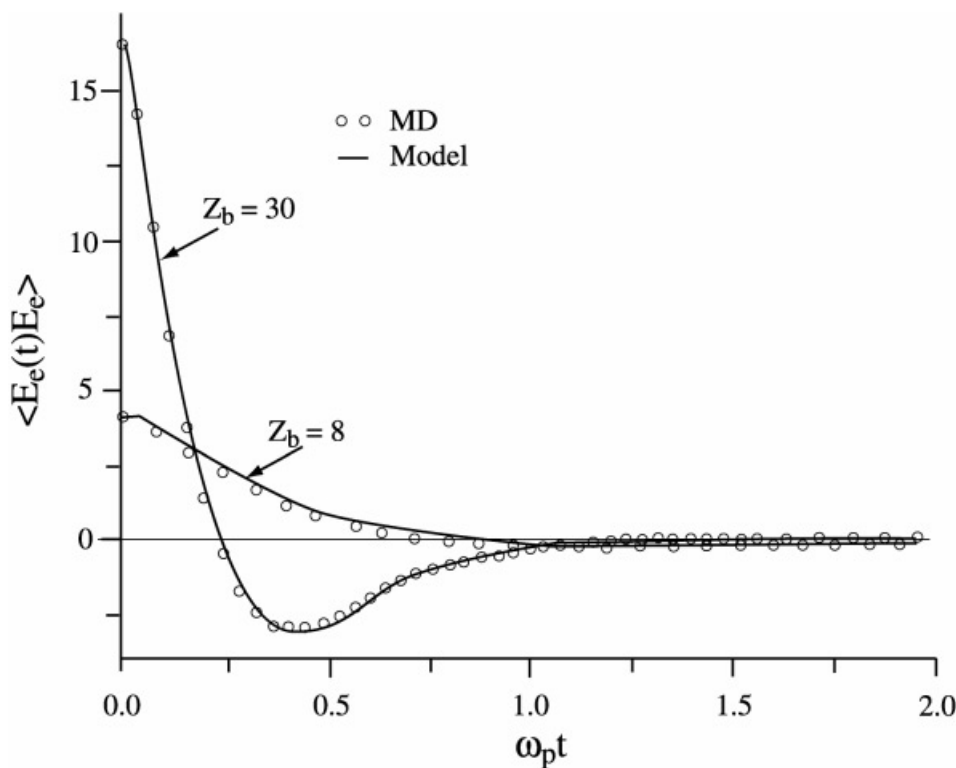

Fig. 2. Comparison of $C(t)$ from MD and from equation for $Z_b = 8$ and 30 at $\Gamma = 0.1$ and $\delta = 0.4$ (From Dufty *et al.*, 2003).

where $\delta = (2\pi\hbar^2/2m_e k_b T_e)^{1/2}$ refers to target electron thermal De Broglie wavelength. In Figure 2, $C(t)$ refers to the dimensionless expression

$$C(t) = \frac{a^4}{e^2} \langle \vec{E}_e(t) \cdot \vec{E}_e \rangle, \qquad (12)$$

in terms of mean inter-electron distance a.

It should be appreciated that Z_b high values lead to an anti-correlation ($C(t) < 0$) for $0.25 < \omega_p < 1$, ω_p denoting target electron plasma frequency. This feature highlights an arbitrarily strong coupling between low velocity ion projectile and target electrons. This coupling may be expressed by Eq. (11)
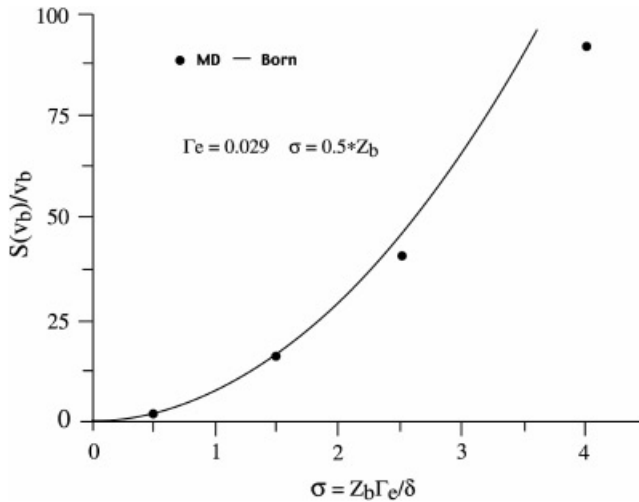
$$\sigma = \frac{V(0)}{k_B T_e} = \frac{Z_b \Gamma_e}{\delta}, \quad \text{where } \Gamma_e = \frac{e^2}{k_B T_e r_0}. \qquad (13)$$

Contrasting again in Figure 3, MD simulation results with analytic ones, both are based on Eq. (11). One can witness a nearly parabolic rise of $S(V_b)/V_b$ in terms of coupling σ. It would be highly desirable to extend such investigations to any Γ_e values.

4. LOW VELOCITY PROJECTILE IN DENSE PLASMA

In the present context, it appears useful to make contact with numerical simulations tracking the low velocity ion projectile in the dense target plasma. Rather instructive ones are just been offered by a group from the Tokyo Institute of Technology (Oguri *et al.*, 2005).

These authors have thus numerically investigated the stopping power of low-energy, highly charged projectiles in cold dense plasmas in order to determine realistic parameters for beam-plasma interaction experiments with low

energy (10–100 keV/a.m.u) ion projectiles delivered by a 1.7 MV electrostatic accelerator. They used a simple MD computer code and observed that for projectile velocity as low as thermal electron velocity, in a sufficiently high charge state, non linear stopping as advocated above can be witnessed even for a weakly coupled plasma target with $\Gamma_e \cong 0.1$ (see Fig. 4).

It should be noticed that projectiles with such high charge state rapidly disappear through a strong recombination with target electrons conveying the ion projectile, even in the absence of residual hydrogen atoms in the plasma. These can prove very efficient in transferring their bound electrons to the incoming ion, even at very high dilution.
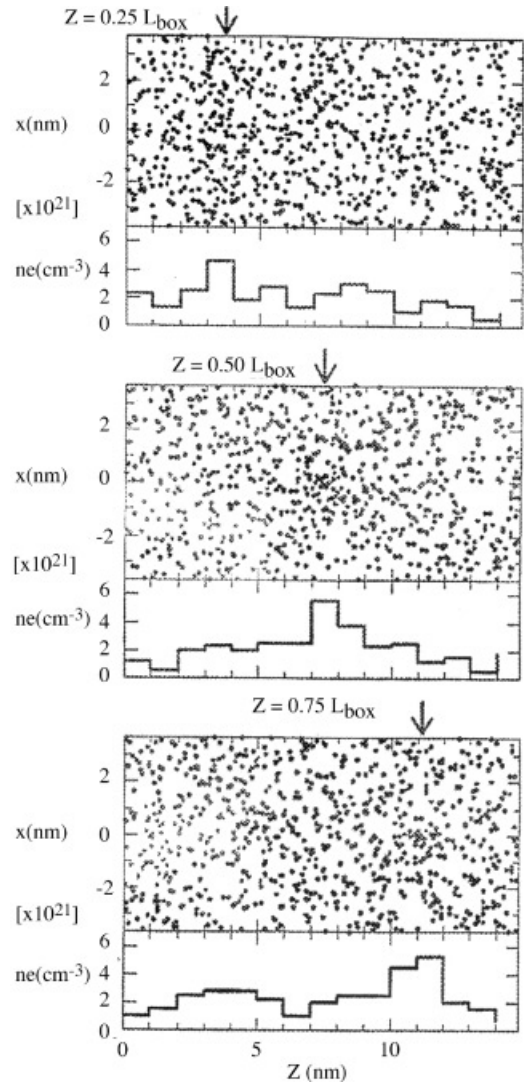
Fig. 4. Framing images of plasma electrons and electron density distributions along the z-axis for three different projectile positions. The outer frames show the wall of the box. A 20 keV/u^{93}Nb^{40+} projectile was injected into the plasma from the left side at $x = y = z = 0$. The arrows show the longitudinal positions of the projectile. The electron density and temperature of the target plasma are 10^{21} cm^{-3} and 10 eV, respectively. The axial electron density distribution was calculated for a paraxial region of -1 nm $< x < 1$ nm and -1 nm $< y < 1$ nm (From Oguri *et al.*, 2005).

Fig. 3. Stopping power vs coupling for moderate coupling conditions (From Dufty *et al.*, 2004).

5. PROSPECTIVE REMARKS

This rather sketchy presentation of the US beam-target program, highlights its content in rejuvenated questioning for the field of ion stopping in matter. Among the most urgent and challenging inquiries, let us retain:

- Projectile effective charge near end of range
- Inflight projectile spectroscopy
- Strong Coulomb correlations in target → WDM
- Ion multiple scattering and straggling
- Superelastic contribution to low V_b ion stopping
- Validation of global sum rule for arbitrary ion beam distribution
- Projectile excitation (Z projectile > Z target).

ACKNOWLEDGMENT

REFERENCES

DEUTSCH, C. (1986). Inertial confinement fusion-driven by intense ion beams. *Annales de Phys.* **11**, 1.

DEUTSCH, C., MAYNARD, G., BIMBOT, R., GARDES, D., DEL-LANEGRA, S., DUMAIL, M., KUBICA, B., RICHARD, A., RIVET, M.F., SERVAJEAN, A., FLEURIER, C., SANBA, A., HOFFMANN, D.H.H., WEYRICH, K. & WAHL, H. (1989). Ion beam-plasma interaction—a standard model approach. *Nucl. Instr. & Meth. Phys. Res. A* **278**, 38–43.

DEUTSCH, C. & MAYNARD, G. (2000). Stopping of pointlike charges in a dense electron fluid. *Recent Res. Dev. Plasmas* **1**, 1.

DEUTSCH, C. (1977). Nodal expansion for a real matter plasma. *Phys. Lett A* **60**, 317.

DUFTY, J.W., TALIN, B. & CALISTI, A. (2004). High Z ions in hot, dense matter. *Adv. Quan. Chem.* **46**, 293.

DUFTY, J.W., PEGORELOV, T.V., TALIN, B. & CALISTI, A. (2003). Nonlinear response of electron dynamics to a positive ion. *J. Phys. A* **36**, 6057.

FORSTER, D. (1975). *Hydrodynamic Flustuations, Broken Symmetry, and Correlation Functions*. Reading, MA: W. Benjamin.

GOLDSTON, R.J. & RUTHERFORD, P.H. (1995). *Introduction to Plasma Physics*. Bristol, PA: Institute of Physics Publishing.

GRISHAM, L.R. (2004). Moderate energy ions for high energy density physics experiments. *Phys. Plasmas* **11**, 5727.

HOFFMANN, D.H.H., WEYRICH, K., WAHL, H., GARDES, D., BIMBOT, R. & FLEURIER, C. (1990). Energy-loss of heavy-ions in a plasma target. *Phys. Rev. A* **42**, 2313–2321.

LOGAN, B.G., BIENIOSEK, F.M., CELATA, C.M., HENESTROZA, E., KWAN, J.W., LEE, E.P., LEITNER, M., ROY, P.K., SEIDL, P.A., EYLON, S., VAY, J.L., WALDRON, W.L., YU, S.S., BARNARD, J.J., CALLAHAN, D.A., COHEN, R.H., FRIEDMAN, A., GROTE, D.P., COVO, M.K., MEIER, W.R., MOLVIK, A.W., LUND, S.M., DAVIDSON, R.C., EFTHIMION, P.C., GILSON, E.P., GRISHAM, L.R., KAGANOVICH, I.D., QIN, H., STARTSEV, E.A., ROSE, D.V., WELCH, D.R., OLSON, C.L., KISHEK, R.A., O'SHEA, P., HABER, I. & PROST, L.R. (2005). Overview of US heavy ion fusion research. *Nucl. Fusion* **45**, 131.

NG, A., AO, T., PERROT, F., DHARMA-WARDANA, M.W.C. & FOORD, M.E. (2005). Idealized slab plasma approach for the study of warm dense matter. *Laser Part. Beams* **23**, 527–537.

OGURI, Y., HASEGAWA, J., KANEKO, J., OGAWA, M. & HORIOKA, K. (2005). Stopping of low energy highly charged ions in dense plasmas. *Nucl. Instr. & Meth. Phys. Res. A* **544**, 76.

PAUL, H. & SCHINNER, A. (2003). Judging the reliability of stopping power tables and programs for heavy ions. *Nucl. Instr. & Meth. Phys. Res. B* **227**, 461.

TALIN, B., DUFOUR, E. CALISTI, A., GIGOSOS, M.A., GONZALEZ, M.A., GAZTELURRUTIA, D. & DUFTY, J.W. (2003). Molecular dynamics simulation for modeling plasma spectroscopy. *J. Phys. A* **36**, 6049.