Laser and Particle Beams (2002), *20*, 467–470. Printed in the USA.

DOI: 10.1017/S0263034602203213

Swift heavy ions in dense plasmas: The interaction process as a probe of the plasma properties

GILLES MAYNARD
Laboratoire de Physique des Gaz et des Plasmas, bât. 210, Université, Paris XI, CNRS-UMR8578, F-91405 Orsay, France

Abstract

In this article, we analyze the sensitivity of the charge and energy distribution of a swift heavy ion beam interacting with a dense plasma on the thermodynamic and dynamic properties of the target. We study more particularly partially ionized carbon targets in which both the bound and the free electrons yield a significant contribution to the stopping. The emphasis is put on direct and indirect correlation between charge transfer and stopping. We show that nonlinearities, appearing in the interaction process for heavy ions, increase the dependency of the stopping on the plasma properties, indicating that diagnostics based on the analysis of the beam ions can provide valuable information on the target properties.

Keywords: Dense plasmas; Heavy ions; Stopping power

1. INTRODUCTION

Beam–plasma interaction experiments and theoretical works on the energy loss and charge evolution of swift heavy ions interacting with a dense plasma, as presented in the present and previous proceedings of HIIF conferences, have led to a good understanding of the ion–plasma interaction process. Moreover new diagnostic techniques are being developed (Rosmesj, 2002) to determine the charge distribution of the beam inside the plasma, thus completing the information already available on the charge and energy distribution of the beam ions after they interact with the target. It is thus important to combine the last theoretical and experimental progress to extract the maximum detail information on the physical phenomena occurring when a high-energy heavy ion beam interacts with a plasma target.

Diagnostics of thin cold targets with an energetic beam of well-collimated particles (electrons or ions) are standard techniques to obtain detailed radiographies of the target. In the present article, we address the case of much thicker targets, for which the multiple scattering collisions prevent analysis of each ion trajectory. So our purpose is to determine how much the statistical properties of the beam, such as its distribution of charge or its average energy, are sensitive on the target properties. In particular, we give results on the influence of density, ionization, and nonideality of the target on the average charge and energy loss of heavy ions at several MeV/*n* energies.

The emphasis is put on the variation of this influence with the strength of the projectile–target interaction. At first sight, one can think that an increase of the strength of the binary interaction between the projectile and a target electron, induced by an increase of the projectile atomic number at a fixed velocity, will lead to a reduction of sensitivity of the stopping process, because the projectile–electron interaction will dominate the interparticle potential between the target particles. The purpose of this work is to demonstrate that the reverse situation occurs: At MeV/*n* energies, the stopping of an heavy ion is more sensitive to collective effects than it is for a light projectile.

The calculations presented here have been performed in a high-density carbon target, either cold or at a temperature of 1–50 eV, the plasma being only partially ionized. In particular, the strongly bound 1*s* electrons are still playing the dominant role for electron capture by the projectile. These targets are similar to the plasmas that can be created by high-current ion beams, such as in the SIS100 project at Gesellschaft für Schwerionenforschung, Darmstadt, which is planned to be used to study dense plasma physics. They are dense strongly coupled plasmas, in which the free and the bound electrons have the same order of magnitude contribution to the stopping power.

Our Parametric Average Correlated Atom Model (PACAM) code (Maynard *et al.*, 2002) has been used to

Address correspondence and reprint requests to: G. Maynard, Laboratoire de Physique des Gaz et des Plasmas, bât. 210, Université Paris XI, CNRS–UMR8578, F-91405 Orsay, France. E-mail: Gilles.Maynard@lpgp.u-psud.fr

describe the ion–plasma interaction at high energies and for dense targets. It yields the evolution of the average configuration of the beam ions inside the target.

The stopping cross section S of partially ionized heavy ions have been determined within the CKLT theory (Maynard *et al.*, 2001). In Figure 1, we have represented a typical example of our results for the charge dependent stopping cross section of a swift, heavy ion in matter, together with the Q^2 scaling law (Q2SL) values. We see on the figure that the slope of the CKLT curve is smaller than the Q2SL curve one. The two curves cross at a charge value close to the average charge $\langle Q_g \rangle$ of the ion in a neutral gas. For higher charges, high-order corrections reduce the stopping; thus the CKLT cross section becomes smaller than the Q2SL one. In contrast, for Q less than $\langle Q_g \rangle$, the partial screening of the bound electrons yields the dominant correction over the linear pointlike approximation, and the CKLT result is now larger than the Q2SL one. This result is of general nature for a partially ionized heavy ion in a partially ionized target.

The correction that has to be added to the Q2SL result increases with the difference between the charge of the ion and $\langle Q_g \rangle$. So it is quite small in a cold gas but can be significant in solids or dense plasmas, in which the average charge can be much higher than $\langle Q_g \rangle$.

2. DENSITY AND TEMPERATURE INFLUENCES ON THE CHARGE DISTRIBUTION

It is well known that, for heavy ions at several MeV/*n*, a solid foil leads to higher charge states than a gas stripper (keeping apart the special case of hydrogen), the difference between the two average charges being quite large for the heaviest projectiles. For many years, the question arose, however, about the difference between the charge inside the target and the charge as given by the detector well after the interaction with the foil. In particular, there was great uncertainty about the number of Auger electrons that can be emitted by the projectile at the exit surface of the foil. It is now well accepted that the number of these electrons is small (Maynard *et al.*, 2000). This has two important consequences. First it means that the measured charges outside the target can provide good information on the charge distribution of the beam inside the target. And second, it indicates that, when going from the gas state up to the solid state, the average charge of swift, heavy ions inside the target can be enhanced by several units leading, as shown in Figure 1, to large nonlinear effects. The charge distribution can then be used to get information on the density value of the target. It is thus of practical importance to determine the relative variation of the average charge with the target density.

In Figure 2, we have reported the PACAM results for the average charge of xenon ions in cold carbon targets having the density of ρ_0, $10^{-2}\rho_0$, and $10^{-4}\rho_0$, with ρ_0 being the density of the solid target. We see that the variation of the average charge with the density is quite significant, being 4 units between ρ_0 and $10^{-2}\rho_0$ and of 3 units between $10^{-2}\rho_0$ and $10^{-4}\rho_0$. This variation increases with the atomic number of the projectile, but it is rather independent of the projectile energy in our domain. Thus, using heavy projectiles, the heaviest yielding the highest effects, the charge state distribution of the ion inside the target is quite sensitive to the target density in the range between $10^{-3}\rho_0$ and ρ_0.

The variation of the charge state distribution with the plasma ionization state is also reported in Figure 2. The temperature at each density has been adjusted so that the mean ionization state of the carbon atom is C^{4+}. We observe in this figure that the dependency of $\langle Q \rangle$ on the target temperature is much smaller than on the density. There is nearly no effect at $10^{-2}\rho_0$, a small decrease of $\langle Q \rangle$ at $10^{-4}\rho_0$ and an increase at ρ_0. The two small effects are due to a variation of the capture cross section induced by the

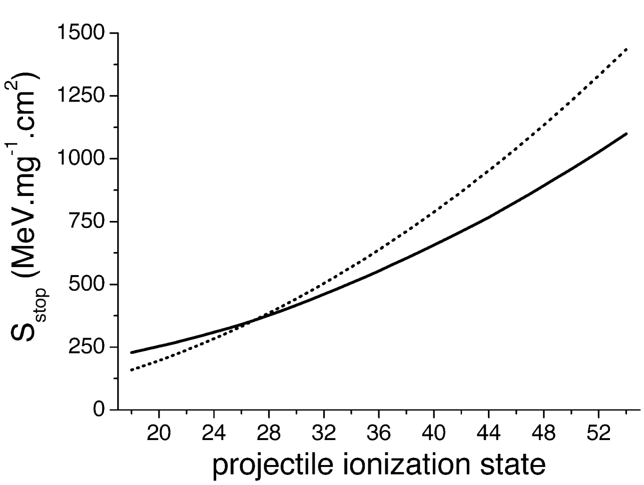

Fig. 1. Stopping cross section versus the ionization state of a 4 MeV/n Xe ion interacting with a carbon plasma at a density of one hundredth of the solid density and at a temperature of 50 eV. Solid line: our CKLT results; dotted-line: Q^2 scaling law result.

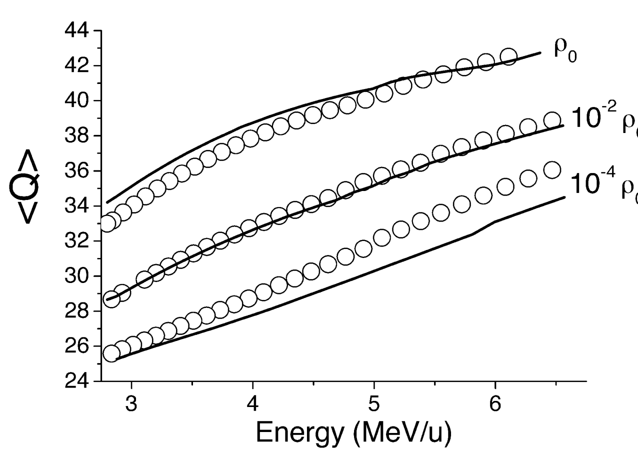

Fig. 2. Average charge of Xe at three densities for a carbon target either neutral or ionized. In the plasma case, the carbon ions are in the helium-like state C^{4+}. Circles: cold target values; solid line: plasma target.

https://doi.org/10.1017/S0263034602203213 Published online by Cambridge University Press

variation in the binding energy of the two bound electrons. At $10^{-4}\rho_0$, the binding energy of the 1*s* electron of C^{4+} is slightly larger than in the neutral atom; thus the capture cross section is enhanced. At ρ_0, a significant part of the bound electrons are in excited states, yielding a reduced capture cross section, while at $10^{-2}\rho_0$, the two effects compensate nearly perfectly.

Looking at the density effect, we have also analyzed the influence of nonideality in the free electron stopping power, determining what the contribution of nonlinearities can be in the variation of the stopping with the nonideality of the free electrons. To get a rough estimate of this effect, we have compared the stopping cross section values when using either a zero collision frequency or a collision frequency equal to the plasma frequency. The obtained result is reported in Figure 3, for a large range of charges of a Xe ion at 4 MeV/*n*, together with the Q2SL value. We see that the Q2SL leads to a reduction of the stopping by collisions of 7%. This reduction is slightly increased by nonlinearities for the highest charges, as shown by the CKLT results, being close to 10% at $Q = 54$. Therefore, considering target nonidealities, the nonlinearities increase the variation of the projectile–target interaction strength with the target properties.

3. VARIATION OF THE ENERGY LOSS WITH THE PLASMA AVERAGE IONIZATION

We report in Figure 4, the CKLT results for the plasma enhancement factor $S(\text{plasma})/S(\text{neutral})$ together with the Q2SL values, for Xe and Zn ions interacting with a carbon target in which, for the plasma case, the carbon ions are in the C^{4+} state and the free electrons density is $n_e = 10^{20}$ cm^{-3}. The figure clearly exhibit the influence of the strength of the interaction, which increases with the charge of the projectile, showing that nonlinearities yield a higher sensitivity of the stopping on the plasma ionization state. The nonlinearities' contribution is larger for Xe (Fig. 4a) than for Zn (Fig. 4b). In the latter case, the contribution of the electrons bound to the projectile compensates for a large part of the nonlinear one.

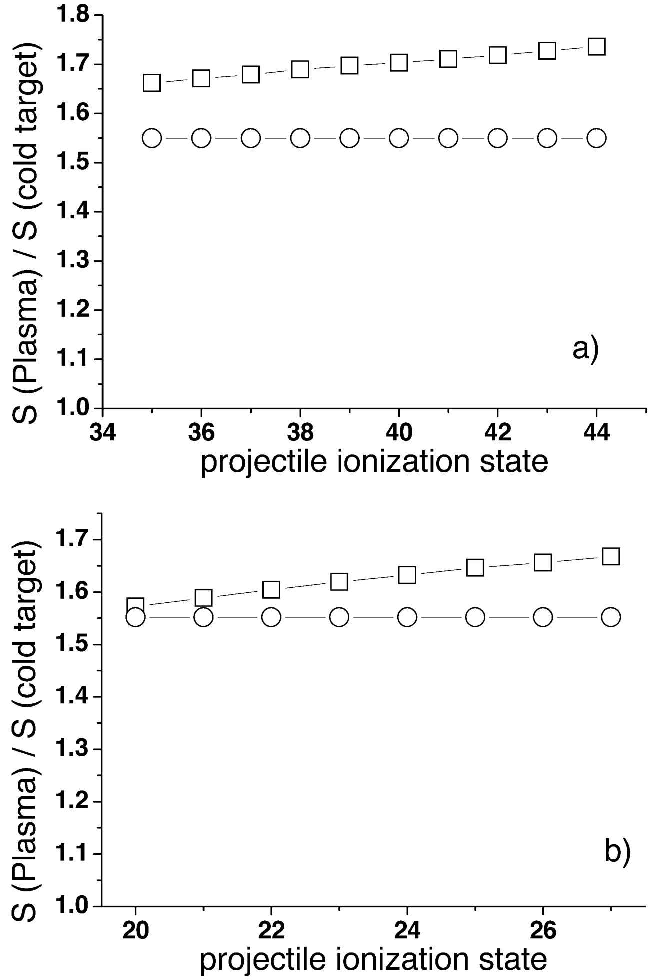

Fig. 4. Plasma enhancement factor for the stopping cross section of Xe (a) and Zn (b) ions in a carbon plasma with a free electron density of $n_e = 10^{20}$ cm^{-3}. Squares: our CKLT values; circles: Q^2 scaling law values.

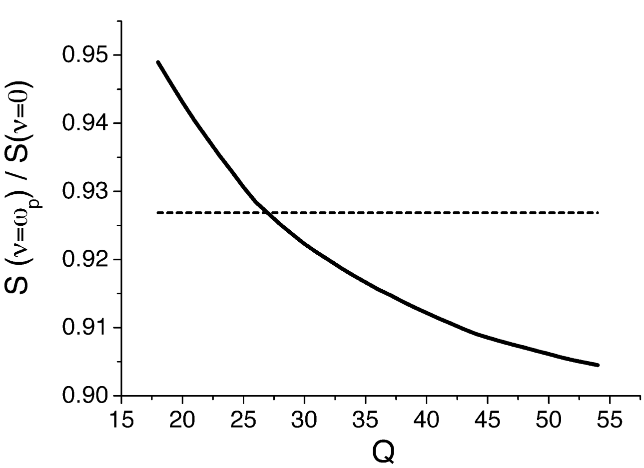

Fig. 3. Ratio between two stopping cross sections values of 4 MeV/*n* Xe in a carbon plasma. The two cross sections are calculated by assuming either that the collision frequency is zero, or that it is equal to the plasma frequency. The plasma density and temperature are as in Figure 1. Solid line: our CKLT result; dotted line: Q^2 scaling law value.

4. CONCLUSION

Our analysis of heavy ions at several MeV/*n* energies interacting with a partially ionized dense plasma demonstrates that the average values of the physical characteristics of the beam are sensitive enough to the plasma state to be used for diagnostic purposes. The average charge is of more concern with the target density while the energy loss is more directly related to the ionization state of the plasma. Our main result is to show that beside the information obtained from the projectile charges, the energy loss process of heavy ions is also more sensitive to the target properties than it is the case for light projectiles. So the nonlinearities increase instead of decreasing the relative variation, between two states of the target, of the stopping cross section.

REFERENCES

MAYNARD, G., CHABOT, M. & GARDES, D. (2000). Density effect and charge dependent stopping theories for heavy ions in the intermediate velocity regime. *Nucl. Instrum. Methods Phys. Res. B* **164–165**, 139–146.

MAYNARD, G., DEUTSCH, C., DIMITRIOU, K., KATSONIS, K. & SARRAZIN, M. (2002). Evaluation of the energy deposition profile for swift heavy ions in dense plasmas. *Nucl. Instrum. Methods Phys. Res. B* **195**, 188–215.

MAYNARD, G., ZWICKNAGEL, G., DEUTSCH, C. & KATSONIS, K. (2001). Diffusion-transport cross section and stopping power of swift heavy ions. *Phys. Rev. A* **63**.

ROSMESJ, F.B., MORE, R., ROSMESJ, O.N., WIESER, J., BORISENKO, N., SHEVELKO, V.P., GEIßEL, M., BLAZEVIC, A., JACOBY, J., DEWALD, E., ROTH, M., BRAMBRINK, E., WEYRICH, K., HOFFMANN, D.H.H., GOLUBEV, A.A., TURTIKOV, V., FERTMAN, A., SHARKOV, B.YU., FAENOV, A.YA., PIKUZ, T.A., MAGUNOV, A.I. & SKOBELEV, I.YU. (2002). Methods of charge-state analysis of fast ions inside matter based on their X-ray spectral distribution. *Laser Part. Beams* **20**, 479–483.

https://doi.org/10.1017/S0263034602203213 Published online by Cambridge University Press