Reply to ''Comment on 'Stopping power of nonmonochromatic heavy-ion clusters with two-ion correlation effects' ''

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In this Reply it is claimed that, although in the Comment by Tkachenko, Muñoz-Cobo, and Muñoz, a full random-phase (RP) analysis of the problem of the stopping power of an expanding charged ion cluster is presented, the main conclusions drawn by these authors are substantially identical to those of our paper [Phys. Rev. E **51**, R2755 (1995)], where only collective effects were considered. Indeed, the strong enhancement of the stopping power of the ion cluster with respect to that evaluated for the same number of uncorrelated projectiles at high velocity, and the decreasing two-ion correlation effect for increasing velocity spread and interaction time, are already predicted in our paper. The full RP approximation makes the behavior of the stopping power at slightly suprathermal velocities more regular. [S1063-651X(97)00411-X]

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The authors of the Comment, Tkachenko, Muñoz-Cobo, and Muñoz (TMM), on Ref. [1] present the results of a numerical computation of the stopping power of an ensemble of $N \gg 1$ ions moving in a plasma. The analysis is carried out in the frame of the full random-phase approximation (RPA). Their computation is performed following the same model proposed in Ref. [1], however, giving up the restriction of considering only the collective effects in the determination of the global stopping power of the charged cluster.

TMM claim that (a) the average stopping power $\langle -dE/dx \rangle_N$ versus the center-of-mass velocity of the cluster is a definite positive function and presents no oscillations; (b) an enhancement of the stopping power is found compared with the case of the same number of uncorrelated charged particles; (c) the energy losses depend only on the product $\Delta r = \Delta v t$, Δv being the velocity spread of the ensemble of charges around the center-of-mass speed, and decrease with increasing Δr; and (d) '' . . . to achieve stronger enhancement . . . one should employ relatively slow ($v \approx 2 \times 10^9$ cm/s) well-packed clusters with as low a velocity dispersion as possible.''

First of all, we wish to point out that indeed an error in the normalization of Eq. (11) of Ref. [1] has occurred. It reads correctly

$$f(\mathbf{r}_{ij}) = \frac{3}{4\pi \Delta \ell^3} H(r_{ij}) H(\Delta \ell - r_{ij}).$$

As a consequence there the correlation effects have been underestimated by a factor of 2.

Let us reply to the points raised in the Comment. As is stated clearly in Ref. [1], there the computation is performed in the limit of large cluster velocity $V_0/v_{\mathrm{the}} \gg 1$, where V_0 and $v_{\mathrm{the}} = \sqrt{T_e/m_e}$ are the center-of-mass and electron thermal speeds, respectively. Here T_e and m_e are the temperature and the mass of the electrons. Consistently with this assumption, the individual particle contribution to the correlation function has been neglected. The validity of the high velocity limit and of retaining only collective effects have been discussed previously in several papers (see, for example, Refs. [2–5]). Oscillations in the stopping power vs particle velocity are observed at low projectile velocities (up to a few times v_{the}), and are due to the wave nature of the long-range interaction between correlated charges. In particular, in Refs. [2,5] negative values of the correlation (or *vicinage*) functions are obtained (in these works, the results of the high velocity limit are compared with those of the full RPA), while in Refs. [3,4] [see Fig. 14(b) of [4], negative stopping powers of groups of charged particles are presented. Oscillations at small velocities can be observed in all these papers.

Physically, the problem can be posed in the following terms: how can two charged particles, whose distance is much larger than the minimum impact parameter $b_{\pi/2} = Z_{\mathrm{eff}} e^2 / m_e V_0^2$, mutually interact while moving in a *classical* plasma so as to be affected globally by a strongly enhanced friction? In the above definition of $b_{\pi/2}$, e is the electric charge of an electron and Z_{eff} is the effective charge of the projectile ion. Of course, this effect of two-particle correlation cannot come from large wave numbers (larger than $b_{\pi/2}^{-1}$). Their contribution and consequently also that of low phase velocities are strongly Landau damped over a short scale.

Most of the contributions to two-ion correlations must come from wave numbers which are much smaller than $b_{\pi/2}^{-1}$, that is, of the order of or smaller than $\lambda_{\mathrm{De}}^{-1}$($\lambda_{\mathrm{De}} = \sqrt{T/4\pi n e^2}$ is the Debye length).

On the other hand, as is well known, the higher the projectile velocity, the longer the wavelengths excited behind it in the form of a Cherenkov wake. A good estimate of the relevant wave numbers can be $k \approx (v_{\mathrm{the}}/V_0)\lambda_{\mathrm{De}}^{-1}$. This is just the reason for the occurrence of the largest correlation effects at high velocities (see Fig. 2 of [1]).

While the Comment contains a more rigorous evaluation of the stopping power for thermal and slightly suprathermal projectiles, where the model of Ref. [1] actually loses its validity, in the high velocity interval (say for $V_0 \geq 10 v_{\mathrm{the}}$) our computation of the stopping power should give correct results. We observe that for $T_e = 20$ eV (as in Fig. 4 of [1]) and

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for $T_e = 300$ eV (as in Fig. 5 of [1]) the electron thermal velocities are $v_{\mathrm{the}} \cong 1.9 \times 10^8$ cm/s and $v_{\mathrm{the}} \cong 7.3 \times 10^8$ cm/s, respectively. Therefore our results strictly hold on the right hand side of the two plots.

The full RPA being correct at low velocity, it is reasonable that it describes a positive stopping power. However, the oscillations of the stopping power with increasing projectile velocity are not unphysical by themselves. They are the ''memory'' of the long-range two-ion correlation through the Cherenkov wake by which any fast charge is followed (see, for example, Ref. [6]). Then, depending on the distance $\Delta r = \Delta v t$ between close particles in the cluster, they can be more or less pronounced in the plot of the stopping power. Points (b) and (c) claimed by TMM are already present in Ref. [1], and the analysis performed in the Comment represents their confirmation.

About point (d), one should be careful in claiming that ''. . . to achieve stronger enhancement . . . one should employ relatively slow well-packed clusters . . . ''. Both full RPA and collective plasma models are linear. If one considers slow and very close projectiles, locally the expansion parameter $Z \equiv Z_{\mathrm{eff}}/[N_D(1+V_0^3/v_{\mathrm{the}}^3)]$, whose smallness allows the linearization of the Vlasov-Poisson system, can become of the order of unity and a nonlinear approach is required.

In conclusion, the results contained in the Comment add new light to the two-ion correlation effects on the stopping power of a charged cluster at slightly suprathermal projectile velocity. As far as suprathermal projectiles are concerned, however, the picture outlined in Ref. [1] still remains valid and the results claimed by TMM actually confirm what has already been found in the paper commented on.

[1] M. Lontano and F. Raimondi, Phys. Rev. E **51**, R2755 (1995).
[2] M. Vicanek, I. Abril, N. R. Arista, and A. Gras-Marti, Phys. Rev. A **46**, 5745 (1992).
[3] J. D'Avanzo, M. Lontano, and P. F. Bortignon, Phys. Rev. E **47**, 3574 (1993).
[4] C. Deutsch, Phys. Rev. E **51**, 619 (1995).
[5] E. M. Bringa and N. R. Arista, Phys. Rev. E **52**, 3010 (1995).
[6] Th. Peter, J. Plasma Phys. **44**, 269 (1990).