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

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We reconsider the results of Lontano and Raimondi [Phys. Rev. E **51**, R2755 (1995)] within the full random-phase approximation. We show that the correlation and also velocity dispersion of the cluster ions enhance and reduce the stopping power, respectively. Nevertheless, the enhancement of energy losses due to ionic correlation is much stronger than that obtained by Lontano and Raimondi, and furthermore, the projectile velocity dependence of the stopping power is strictly monotonic, presenting no oscillations. We also did not obtain negative values for the cluster stopping power, as did Lontano and Raimondi.
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An interesting perspective and approach to inertial confinement fusion (ICF), proposed in [1,2], is being studied recently in a number of articles (see [3], and references therein) on stopping power of heavy-ion clusters in ICF plasmas.

The Lontano and Raimondi paper [3] deals with the possible stopping power enhancement due to correlation effects between cluster ions. The ion velocity dispersion effect (Cherenkov decorrelation) is also discussed there.

The stopping power of 10^3 heavy (Pb or Bi) ions in Z-pinch and ICF relevant warm plasmas was calculated in [3] in the $(1-7)\times 10^4$ km/s projectile velocity range. The projectiles were assumed to be almost monochromatic and uniformly distributed in the physical space within a given volume. The plasma dielectric function was estimated in the ''warm plasma'' kinetic approximation. In addition only excitation of collective modes with wavelengths larger than the Debye screening length was taken into account.

Significant enhancement of projectiles' energy losses was shown for certain values of the cluster (projectile) velocity and radius.

An unexplained nonmonotonic dependence of the cluster stopping power for alternative values of the projectile velocity and radius was obtained. Conditions were found for the stopping power taking negative values (plasma cooling?).

We have thoroughly studied the projectile velocity dependence of the cluster stopping power, especially in the case of Fig. 4 of [3] both in the full random-phase approximation (RPA) and using the approximations (collective approximation, warm plasma approximation) of [3], and our results are the following.

Due to an error involved in Eq. (11) of the paper [3], we could not exactly reproduce the theoretical curves provided in it. The distribution function defined by Eq. (11) is not normalized to unity.

Nevertheless, these curves are reproduced almost quantitatively as soon as the warm plasma expression is employed for the plasma dielectric function in our formulas. We used the spatial averaging procedure suggested in [3]. In addition we evaluated the influence on the stopping power by the velocity dispersion of cluster ions, also presuming a homogeneous velocity distribution of [3]; see Figs. 1(b) and 2(b). Notice that our Figs. 1 correspond to the conditions of Fig. 4 of [3], and our Figs. 2 to those of Fig. 5 of [3].

As was expected, the energy losses effectively depend only on the effective radius value $\Delta r = \Delta v t$, Δv being a spread around the projectile velocity v, and t the observation time. The energy losses decrease with growing value of Δr.

No significant influence of the collective approximation was observed.

The stopping power of $N = 10^3$ uncorrelated ions was reproduced within both approaches: that of [3] and ours.

We managed also to reproduce an (erroneous) strong oscillatory Δl dependence of the cluster stopping power in the warm plasma approximation. We defined Δl as the cluster radius. Particularly, as in [3], within a certain projectile velocity range, values of Δl were found for which the stopping power oscillated significantly, between positive and negative values.

No physical explanation was provided by the authors of [3] for the stopping power becoming negative. We also did not find reasons for the situation when, at certain values of the cluster linear dimensions and of its mean velocity, the plasma would transfer energy to the cluster. Notice also that for these velocity ranges no clear convergence of the stopping power of correlated clusters to the ''uncorrelated'' values (with growing Δl) takes place.

No such unphysical behavior of the plasma stopping power was observed within the full RPA employed by us, see our Figs. 1 and 2.

We attribute the nonmonotonic projectile velocity dependence of the stopping power to the fact that in the warm plasma approximation used in [3] the real part of the plasma dielectric function is substituted by its high-frequency asymptotic form [4],

$$\mathrm{Re}[\epsilon^{\mathrm{warm}}(k,\omega)] \simeq 1 - \frac{\omega_p^2}{\omega^2}\left(1 + \frac{3k^2 v_{\mathrm{the}}^2}{\omega^2}\right), \qquad (1)$$

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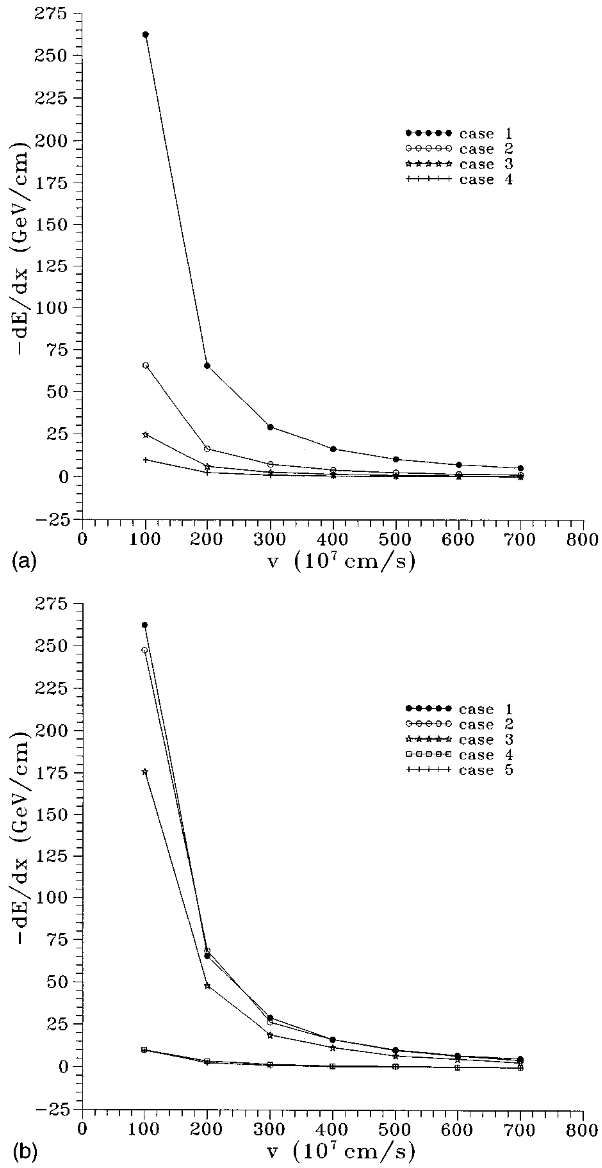

FIG. 1. (a) The stopping power (in GeV/cm) of $N=10^3$ Pb ions, with effective charge number $Z_{\rm eff}=50$, averaged over homogeneous spatial and velocity distributions of [3] vs the projectile velocity v (in 10^7 cm/s), for different values of the cluster volume radius Δl: 0.33 μm (case 1, full circles), 0.66 μm (case 2, open circles), 1.65 μm (case 3, stars). The stopping power of 10^3 uncorrelated ions is also given for comparison (case 4, crosses). The plasma parameters are $n_e=10^{18}$ cm^{-3}, $T_e=20$ eV (corresponding to the electronic Debye radius $\lambda_{\rm De}\simeq 3\times 10^{-2}$ μm, and the average charge number of plasma ions $Z\simeq 1$). The results are calculated for the projectile velocity dispersion spread $\Delta v=0$. (b) As in case 1, $\Delta l=0.33$ μm, but for the projectile velocity dispersion spread $\Delta v\neq 0$. For comparison the curve corresponding to $\Delta v=0$ is reproduced (case 1, full circles). The stopping power effectively depends on the value of the effective radius $\Delta r=\Delta v t$ (see text), and other cases are labeled by the value of Δr:3.31×10^{-8} cm (case 2, open circles), 3.31×10^{-7} cm (case 3, stars), 3.31×10^{-6} cm (case 4, squares). The stopping power of 10^3 uncorrelated Pb ions is also given for comparison (case 5, crosses).

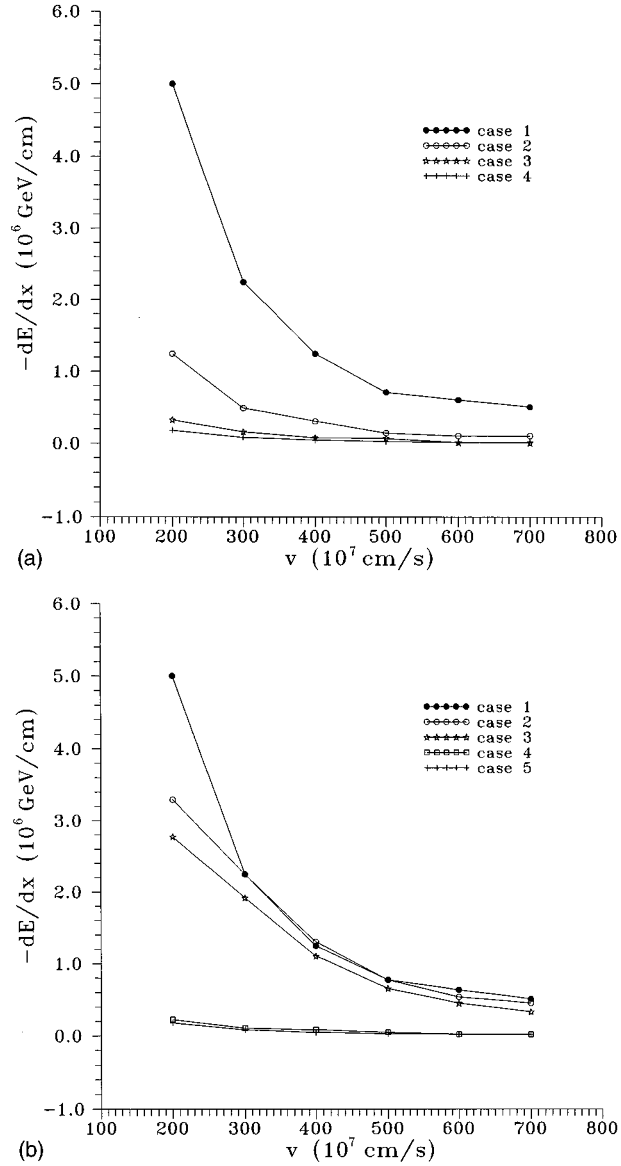

FIG. 2. (a) The stopping power (in GeV/cm) of $N=10^3$ Bi ions, with effective charge number $Z_{\rm eff}=80$, averaged over homogeneous spatial and velocity distributions of [3] vs the projectile velocity v (in 10^7 cm/s), for different values of the cluster volume radius Δl:74.3 Å (case 1, full circles), 148.6 Å (case 2, open circles), 371.5 Å (case 3, stars). The stopping power of 10^3 uncorrelated ions is also given for comparison (case 4, crosses). The hydrogen ICF relevant plasma parameters are $n_e=3\times 10^{22}$ cm^{-3}, $T_e=300$ eV (corresponding to the electronic Debye radius $\lambda_{\rm De}\simeq 7.4$ Å, and the average charge number of plasma ions $Z\simeq 6$). The results are calculated for the projectile velocity dispersion spread $\Delta v=0$. (b) As in (a), case 1, $\Delta l=74.3$ Å, but for the projectile velocity dispersion spread $\Delta v\neq 0$. For comparison the curve corresponding to $\Delta v=0$ is reproduced (case 1, full circles). The stopping power effectively depends on the value of the effective radius $\Delta r=\Delta v t$ (see text), and other cases are labeled by the value of Δr:7.40×10^{-8} cm (case 2, open circles), 740×10^{-7} cm (case 3, stars), 7.40×10^{-6} cm (case 4, squares). The stopping power of 10^3 uncorrelated Bi ions is also given for comparison (case 5, crosses).

ω_p and $v_{\rm the}$ being the plasma frequency and the electronic thermal velocity.

Certainly, as $\omega\rightarrow\infty$ this form coincides with the RPA one but the integration over $\omega=\mathbf{k}\cdot\mathbf{v}$ included in the stopping power calculation incorporates the plasma-frequency zero of Eq. (1) and leads not only to the stopping power oscillations but also to unphysical negative values of the stopping power.

In the full RPA the real part of the dielectric function does not possess this strong frequency behavior, and guarantees the correct averaging over the cluster distribution.

Thus we have demonstrated that the unphysical oscillatory dependence of the cluster stopping power on its linear dimensions and on velocity, as well as the stopping power's negative values (meaning that the plasma cools due to the motion of heavy-ion clusters) stems only from the approximation used by the authors of [3].

The cluster stopping power of Z-pinch and ICF relevant plasmas calculated within the full RPA possesses only a monotonic dependence on the cluster mean velocity, see our Figs. 1(a) and 2(a). An essential enhancement of the plasma stopping power of correlated small ion clusters with respect to that of the same number of uncorrelated ions is shown.

We confirmed a monotonic convergence of the correlated cluster stopping power to that of the same number of uncorrelated ions as (i) the cluster radius Δl [Figs. 1(a) and 2(a)] increases or (ii) the cluster velocity spread Δv increases. See Figs. 1(b) and 2(b).

We conclude that to achieve stronger enhancement of energy losses of ions clusters in warm and hot plasmas, one should employ relatively slow ($v \simeq 2\times 10^9$ cm/s) well-packed clusters with as low a velocity dispersion as possible. No oscillatory behavior of the plasma stopping power as a function of the projectile velocity (as in [3]) is observed.

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