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Laser-assisted stopping power of a hot plasma for a system of correlated ions

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The laser-assisted stopping power of a fully ionized plasma for the system of two correlated test charges is investigated. The general expressions for the stopping power are applied to a low-density and a low-temperature plasma in a low-energy beam-plasma experiment [J. Jacoby *et al.*, Phys. Rev. Lett. **74**, 1550 (1995)]. The effect of the interaction between the beam test charges, described by a correlation term, is to increase the stopping power of the laser-assisted plasma compared to the case where the charges are infinitely separated. However, the laser field affects the correlation between the test charges and contributes to decrease the plasma stopping power, as compared to the laser-free dicluster case. [S1063-651X(99)02912-8]

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I. INTRODUCTION

After the pioneering works of Bohr [1], Bethe [2], and Bloch [3], the related subjects of energy loss and stopping power have been treated by many authors in different media, such as metals and astrophysical and thermonuclear plasmas. It is worth mentioning the pioneering work of Fermi, which included the density effect of the medium on the stopping power [4]. Currently, this subject has become a classic topic in physics [5–8]. The interested reader can also consult the review report [9].

The energy-loss rate for different physical conditions has already been investigated in many publications. In particular, theoretical models that include the contribution of bound electrons in inertial confinement targets [10] and the effect of interparticle correlations in dense, high-temperature plasmas [11,12], have been developed.

Recently, some authors have revived the interest for these basic processes due to the possibility of using fast and heavy ion beams as drivers in inertial confinement fusion experiments [13–17]. In this context, some authors have also studied the stopping of a high-energy N cluster in dense classical plasma [18] and in dense jellium targets [19].

When an intense electromagnetic field is present, as in laser-produced plasmas, the interaction potential between charged particles in the plasma becomes dynamically screened, particularly at the frequency of the field and its harmonics [20]. This dynamic screening can also change the effective collision frequency for the absorption of electromagnetic waves [21], the energy levels of embedded impurity ions [22], and the stopping power of degenerated [23] and nondegenerated plasmas [24]. Nevertheless, the effect of the dynamic laser screening on the energy-loss rate of correlated motion of fast test ions in fully ionized plasmas has not yet been considered

Some years ago, one of us has calculated the effect of an intense electromagnetic field on the energy-loss rate of an ion moving in a fully ionized nondegenerate plasma [24]. In this paper we extend these calculations in order to investigate the more general case of the motion of two test ions and bring out the effects of their correlated motion on the laser-assisted plasma stopping power.

The paper is organized as follows. In Sec. II, by means of Fourier analysis and linearization of the Vlasov-Poisson equations, we derive the general expression of the laser-assisted stopping power for a beam composed of N charges. In Sec. III, the general dicluster expression of the stopping power is analyzed in detail for several particular relevant cases. In Sec. IV we introduce the vicinage function concept, which describes the intensity of correlation effects on the slowing down process. In Sec. V, the general expressions for the dicluster are used to make a parametric analysis of the correlation effect combined with the laser field assistance upon the plasma stopping power. The concluding remarks are presented in Sec. VI.

II. VLASOV-POISSON MODEL AND STOPPING POWER

Let us consider the slowing-down process of a beam composed of N test charges moving in a Maxwellian electron plasma, with a neutralizing background of immobile ions. The system is described by the self-consistent set of Vlasov-Poisson equations. The electron plasma, which is assumed to be initially in equilibrium, is permeated by a long-wavelength electromagnetic field (laser field) taken in the dipole approximations, $\vec{E}_o \sin(\omega_o t)$, where $\vec{E}_o$ is the amplitude and ω_o is the laser frequency. Each particle in the cluster has an effective charge $Z_i^{\mathrm{ef}} e$ (e is the modulus of the electron charge) and a mass M . They move through the plasma with nonrelativistic average velocity $\vec{v}_o$.

In a first approximation, small deviations of the individual velocities from $\vec{v}_o$ are neglected and the charge density, σ, of the cluster, can be written as

$$\sigma(\vec{r},t)=\sum_{i=1}^{N} Z_i^{\mathrm{ef}} e\,\delta(\vec{r}-\vec{r}_i-\vec{v}_o t), \tag{1}$$

where $\vec{r}_i$ are the positions of the test charges at time $t=0$.

The electron distribution function $f(\vec{r},\vec{v},t)$ satisfies the Vlasov equation,

$$\frac{\partial f}{\partial t}+\vec{v}\cdot\frac{\partial f}{\partial \vec{r}}+\frac{e}{m}\left(\frac{\partial \phi(\vec{r},t)}{\partial \vec{r}}-\vec{E}_o\sin(\omega_o t)\right)\cdot\frac{\partial f}{\partial \vec{v}}=0, \quad (2)$$

and the electrostatic potential, $\phi(\vec{r},t)$, is a solution of the Poisson equation,

$$\nabla^2_{\vec{r}}\phi(\vec{r},t)=4\pi e\left\{n_o\int f d\vec{v}-n_o-\sum_{i=1}^{N} Z_i^{\text{ef}}\delta(\vec{r}-\vec{r}_i-\vec{v}_o t)\right\}, \quad (3)$$

where $n_o e$ is the equilibrium charge density of plasma electrons which is equal to the background ion charge density.

Closely following the procedure already outlined in Ref. [24] , Eqs. (2) and (3) can be solved using a canonical transformation to the electron oscillating frame. Resorting to linearization about the equilibrium state and using the standard methods of Fourier analysis, the electrostatic field around the beam test charges is readily found. The slow time variation of the electric field in physical space time, $\vec{E}(\vec{r},t) =-\nabla_{\vec{r}}\phi(\vec{r},t)$, is found using the inverse Fourier transform and then taking the time average over the laser period:

$$\vec{E}(\vec{r},t)=-\frac{1}{(2\pi)^2}\sum_{i=1}^{N} Z_i^{\text{ef}}e\sum_{n=-\infty}^{\infty}\int d\vec{k}\frac{2j\vec{k}}{k^2}e^{j\vec{k}\cdot(\vec{r}-\vec{r}_i-\vec{v}_o t)} \times J_n^2(\vec{k}\cdot\vec{a})\frac{1}{\epsilon(\vec{k},\omega_{\vec{k},n})}, \quad (4)$$

where

$$\omega_{\vec{k},n}=\vec{k}\cdot\vec{v}_o-n\omega_o \quad (5)$$

is the laser harmonic Doppler shifted frequency, $J_n(x)$ are Bessel 's functions of the first kind, $\vec{a}=e\vec{E}_o/m\omega_o$ is the electron oscillation amplitude in the laser field, and

$$\epsilon(\vec{k},\omega)=1+\frac{\omega_p^2}{k^2}\int d\vec{u}\frac{\vec{k}\cdot\partial f^{(o)}/\partial\vec{u}}{\omega-\vec{k}\cdot\vec{u}} \quad (6)$$

is the well known plasma dielectric function [5].

The force acting on the mth particle of the beam is given by

$$\vec{F}_m=Z_m^{\text{ef}}e\vec{E}(\vec{r}_m+\vec{v}_o t,t). \quad (7)$$

Now, as explained in Ref. [25], the forces described by the energy-loss function, $\text{Im}[-1/\epsilon(\vec{k},\omega_{\vec{k},n})]$, are dissipative forces and add up to give the plasma stopping power.

The stopping power, $S=-d\varepsilon/dx$, or the energy loss per unit path length, can be calculated as the force component along the direction of the test charges motion:

$$-\frac{d\varepsilon}{dx}=-\frac{1}{v_o}\frac{d\varepsilon}{dt}=-\sum_m\frac{\vec{v}_o}{v_o}\cdot\vec{F}_m. \quad (8)$$

Replacing the expression for the electric field, Eq. (4), in the equation for the force (7), inserting the result of this operation in the above equation, and then taking the real part, the general expression for the stopping power can be put into the form

$$-\frac{d\varepsilon}{dx}=\frac{e^2}{2\pi^2}\left\{I_o+2\sum_{n=1}^{\infty}I_n\right\}, \quad (9)$$

where

$$I_n=\int\frac{d\vec{k}}{k^2}\frac{\vec{k}\cdot\vec{v}_o}{v_o}J_n^2(\vec{k}\cdot\vec{a})\text{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right] \times\left[\sum_{i=1}^{N}(Z_i^{\text{ef}})^2+\sum_{i\neq m}^{N}Z_i^{\text{ef}}Z_m^{\text{ef}}\cos(\vec{k}\cdot\vec{r}_{m,i})\right], \quad (10)$$

and $\vec{r}_{m,i}=\vec{r}_m-\vec{r}_i$ is the relative position vector between the charges m and i. In the above expression, the terms $i=m$, which give the stopping power of totally independent charges, have been separated from the terms $i\neq m$, which represent interference effects on the laser-assisted stopping power due to the simultaneous perturbation of the medium by the charges in correlated motion. Also, in deriving Eq. (9), we have used the parity relations of the plasma dielectric function and of the Bessel functions to equate the sum over negative values of n to the sum over positive values.

III. DICLUSTER PLASMA STOPPING POWER

The integrand of the expression given by Eq. (10) consists of a sum of similar terms. The simplest case corresponds to two charges $Z_1^{\text{ef}}e$ and $Z_2^{\text{ef}}e$ (''dicluster''), in laser-assisted correlated motion with velocity $\vec{v}_o$ and interionic vector $\vec{r}_{2,1}=\vec{l}$. In this case the mentioned expression reads

$$I_n=\int\frac{d\vec{k}}{k^2}\frac{\vec{k}\cdot\vec{v}_o}{v_o}J_n^2(\vec{k}\cdot\vec{a})\text{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right] \times[(Z_1^{\text{ef}})^2+(Z_2^{\text{ef}})^2+2Z_1^{\text{ef}}Z_2^{\text{ef}}\cos(\vec{k}\cdot\vec{l})]. \quad (11)$$

From now on, unless otherwise mentioned, we employ dimensionless variables. These variables are defined through the following natural parameters of the system: electron thermal velocity $v_t=\sqrt{T/m}$ (where T is the electron plasma temperature in units of energy), Debye length $\lambda_D=\sqrt{T/4\pi n_o e^2}$ (or $k_D=1/\lambda_D$), and the electron plasma frequency $\omega_p =\sqrt{4\pi n_o e^2/m}$. The normalized variables are then defined as

$$\begin{aligned}\vec{r}&\equiv\vec{r}/\lambda_D,\\ \vec{k}&\equiv\vec{k}/k_D,\\ \vec{v}_o&\equiv\vec{v}_o/v_t,\\ \omega_o&\equiv\omega_o/\omega_p,\\ t&\equiv t\omega_p,\\ \varepsilon&\equiv\frac{\varepsilon}{T}.\end{aligned} \quad (12)$$

To obtain specific results, we use a reference system with the x axis in the direction of the test particles velocity, i.e., $\vec{v}_o = v_o \vec{e}_x$. The oscillation amplitude $\vec{a}$ is taken in the xy plane making an angle α with the x axis. Then, using spherical coordinates (k,θ,φ) for the $\vec{k}$ variable and cylindrical coordinates $(l_x, l_\perp, \varphi')$ to the interionic vector, $\vec{l} = l_x \vec{e}_x + l_\perp \vec{e}_\rho$, the dicluster equations (9) and (11) can be written as

$$S_{2p} \equiv -\frac{d\varepsilon}{dx} = \frac{N_D}{(2\pi)^3}\left\{ K_o + 2\sum_{n=1}^{\infty} K_n \right\}, \tag{13}$$

with

$$K_n = \int_0^{k_m} dk k \int_{-1}^{1} d\mu \mu \int_0^{2\pi} d\varphi J_n^2(\vec{k}\cdot\vec{a}) \mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right] \times [Z_1^2 + Z_2^2 + 2Z_1 Z_2 \cos(\vec{k}\cdot\vec{l})], \tag{14}$$

where $N_D = n_o \lambda_D^3$ is the Debye number, $Z_i = Z_i^{\mathrm{ef}}/N_D$ is the reduced effective charge, $\mu = \cos\theta$, $\vec{k}\cdot\vec{a} = ka\cos\theta\cos\alpha + ka\sin\alpha\sin\theta\cos\varphi$, $\vec{k}\cdot\vec{l} = kl_x\cos\theta + kl_\perp\sin\theta\cos(\varphi - \varphi')$, and k_m is the cutoff parameter to eliminate the classical Coulomb divergence. This divergence comes from the Vlasov model approximation, which neglects the close collisions between the test ions and the plasma electrons. Usually k_m is taken as the inverse of the classical distance of closest approach calculated with the average quadratic speed $(v_o^2 + 1)^{1/2}$, which gives

$$k_m = \frac{1}{b_{\min}} = \frac{4\pi}{Z}(1 + v_o^2). \tag{15}$$

Initially, we observe that if the laser polarization is parallel to the test charges velocity, $\vec{v}_o$, which means $\alpha = 0$, it is possible to integrate the general expression (14) in the φ variable. In that case the Bessel function argument is $\vec{k}\cdot\vec{a} = ka\mu$ and $\vec{k}\cdot\vec{l} = kl_x\mu + kl_\perp\sqrt{1-\mu^2}\cos(\varphi - \varphi')$. Using the identity

$$\int_0^{2\pi} d\varphi e^{jb\cos(\varphi-\varphi')} = 2\pi J_o(b), \tag{16}$$

we get the particular simplified result

$$K_n = 2\pi \int_0^{k_m} dk k \int_{-1}^{1} d\mu\, \mu J_n^2(ka\mu) \mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right] \times [Z_1 + Z_2 + 2Z_1 Z_2 \cos(l_x\mu) J_o(kl_\perp\sqrt{1-\mu^2})]. \tag{17}$$

Now, several particular cases for the plasma stopping power can be obtained from the general dicluster result (13) and (14). The simplest case corresponds to one test charge moving through the plasma without laser assistance. In this case, setting $\vec{a} = 0$ implies $J_n(\vec{k}\cdot\vec{a}) = \delta_{n,o}$ and, as a consequence, $K_n = 0$ for $n = 1,2,3\ldots.$ Also, setting $Z_1 = 0$ (or $Z_2 = 0$) and integrating over the variable φ, we recover the expression studied by several authors [5,14]:

$$-\frac{d\varepsilon}{dx} = \frac{N_D}{(2\pi)^3} K_o = \frac{N_D Z^2}{(2\pi)^2} \int_0^{k_m} dk\, k \int_{-1}^{1} d\mu\, \mu\, \mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\vec{k}\cdot\vec{v}_o)}\right]. \tag{18}$$

In the same way, the particular case of a dicluster in the absence of a laser field, recently analyzed by D'Avanzo *et al.* [15,16] and by Bringa and Arista [17], can also be found. Taking $Z_1 = Z_2 = Z$, it is seen that

$$-\frac{d\varepsilon}{dx} = \frac{N_D}{(2\pi)^3} K_o = \frac{N_D Z^2}{2\pi^2} \int_0^{k_m} dk\, k \int_{-1}^{1} d\mu\, \mu\, \mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\vec{k}\cdot\vec{v}_o)}\right] \times [1 + \cos(kl_x\mu) J_o(kl_\perp\sqrt{1-\mu^2})]. \tag{19}$$

Finally the case of one test charge moving through a laser-assisted plasma, analyzed by Arista *et al.* [24], is readily found taking $Z_1 = 0$ (or $Z_2 = 0$) in the general expression (14). Using Eq. (13),

$$-\frac{d\varepsilon}{dx} = \frac{N_D Z^2}{(2\pi)^3}\left\{ K_o + 2\sum_{n=1}^{\infty} K_n \right\}, \tag{20}$$

where

$$K_n = \int_0^{k_m} dk\, k \int_{-1}^{1} d\mu\, \mu \int_0^{2\pi} d\varphi J_n^2(\vec{k}\cdot\vec{a}) \mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right]. \tag{21}$$

IV. VICINAGE FUNCTION. COLLECTIVE AND INDIVIDUAL CONTRIBUTIONS

From Eqs. (13) and (14), we identify two contributions to the plasma stopping power. The first one, which has been treated in Ref. [24], comes from the uncorrelated particle motion and corresponds to those terms proportional to Z_1^2 and Z_2^2. The second, which will be systematically treated in this work, comes from the correlated laser-assisted motion of the two ions.

It is useful to introduce the parameter χ, known as the vicinage function [16], which describes the intensity of correlation effects with respect to the completely uncorrelated laser-assisted motion. To define this function, let us first rewrite the dicluster expressions (13) and (14) in the compact form

$$S_{2p} = Z_1^2 S_p + Z_2^2 S_p + 2Z_1 Z_2 S_c. \tag{22}$$

Therefore, defining the vicinage function as

$$\chi = \frac{S_c}{S_p}, \tag{23}$$

Eq. (22) gives

$$S_{2p} = S_p[Z_1^2 + Z_2^2 + 2Z_1 Z_2 \chi]. \tag{24}$$

To get explicitly the vicinage function, we compare this expression with the general expressions (13) and (14) to identify the functions S_c and S_p; then

$$S_p=\frac{N_D}{(2\pi)^3}\left\{I_o+2\sum_{n=1}^{\infty} I_n\right\}, \tag{25}$$

where

$$I_n=\int_0^{k_m}dk\,k\int_{-1}^{1}d\mu\,\mu\int_0^{2\pi}d\varphi J_n^2(\vec{k}\cdot\vec{a})\mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right] \tag{26}$$

and

$$S_c=\frac{N_D}{(2\pi)^3}\left\{L_o+2\sum_{n=1}^{\infty} L_n\right\}, \tag{27}$$

where

$$L_n=\int_0^{k_m}dk\,k\int_{-1}^{1}d\mu\,\mu\int_0^{2\pi}d\varphi J_n^2(\vec{k}\cdot\vec{a}) \times\mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega_{\vec{k},n})}\right]\cos(\vec{k}\cdot\vec{l}). \tag{28}$$

From the above equations, it is seen that if $l=0$, then $L_n=I_n$, $\chi=1$, and $S_{2p}=S_p(Z_1+Z_2)^2$. This last expression means that the two test charges degenerate in one with effective charge equal to Z_1+Z_2. The other limit, $l\to\infty$, implies $L_n\to 0$. Consequently, $\chi\to 0$ and $S_{2p}=S_p(Z_1^2+Z_2^2)$, which corresponds to the plasma stopping power for two free charges.

It is an experimental fact that the interionic vector is randomly distributed. This can be included in the equations introducing a spherical average over the angles (β,φ'), which define the interionic vector orientation. As a result of this average, the function $\cos(\vec{k}\cdot\vec{l})$ in the expression (28) is replaced by the function $\sin(kl)/kl$. Therefore, orientational effects are neglected in this work.

To go further, we have to explicitly determine the contributions from the plasma collective modes in the long-wavelength domain, $k<1$, and that from thermal motion of individual electrons in the short-wavelength domain, $k>1$ [5,24]. In the first domain, the major contribution to the imaginary part of the inverse of the plasma dielectric function comes from the plasma resonances such that

$$\mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega)}\right]=\frac{\pi}{2}[\delta(\omega-1)-\delta(\omega+1)], \tag{29}$$

whereas in the second domain we have

$$\mathrm{Im}\left[\frac{-1}{\epsilon(\vec{k},\omega)}\right]=\sqrt{\frac{\pi}{2}}\frac{k\omega}{(k^2+1)^2}e^{-\omega^2/2k^2} \tag{30}$$

with $\omega=kv_o\mu-n\omega_o$. After some tedious but straightforward algebra, we obtain from Eqs. (27), (28), and (29) the collective contribution to the correlated part of the stopping power, which is given by

$$S_c^{\mathrm{col}}=\frac{N_D}{16\pi^2 v_o^2}\left\{X_o+X_{o2}+2\sum_{n=1}^{N_+}(n\omega_o+1)X_{n2} -2\sum_{n=1}^{N_-}(n\omega_o-1)X_{n1}\right\}, \tag{31}$$

where

$$X_o=\int_0^{2\pi}d\varphi\int_{1/v_o}^{1}\frac{dk}{k}J_o^2\left[-\frac{v_Q}{v_o\omega_o}\cos\alpha +\frac{v_Q}{v_o\omega_o}\sqrt{k^2v_o^2-1}\sin\alpha\cos\varphi\right]\frac{\sin(kl)}{kl}, \tag{32}$$

$$X_{n2}=\int_0^{2\pi}d\varphi\int_{n\omega_o+1/v_o}^{1}\frac{dk}{k}J_n^2\left[\frac{v_Q}{v_o\omega_o}(n\omega_o+1)\cos\alpha +\frac{v_Q}{v_o\omega_o}\sqrt{k^2v_o^2-(n\omega_o+1)^2}\sin\alpha\cos\varphi\right]\frac{\sin(kl)}{kl}, \tag{33}$$

and

$$X_{n1}=\int_0^{2\pi}d\varphi\int_{n\omega_o-1/v_o}^{1}\frac{dk}{k}J_n^2\left[\frac{v_Q}{v_o\omega_o}(n\omega_o-1)\cos\alpha +\frac{v_Q}{v_o\omega_o}\sqrt{k^2v_o^2-(n\omega_o-1)^2}\sin\alpha\cos\varphi\right]\frac{\sin(kl)}{kl}. \tag{34}$$

$N_+=(v_o-1)/\omega_o$ and $N_-=(v_o+1)/\omega_o$ are the integer parts of the real numbers on the right sides and v_Q is the quiver velocity $v_Q=\omega_o a$. In Ref. [24] it was shown that the collective contribution to the stopping power of one test charge vanishes when $v_o<1$. Here the correlated collective contribution given by Eq. (31) also vanishes.

The individual contribution, corresponding to the domain $k>1$, it is given by

$$S_c^{\mathrm{ind}}=\frac{N_D}{2(2\pi)^3}\left\{Y_o+2\sum_{n=1}^{\infty}Y_n\right\}, \tag{35}$$

where

$$Y_n=\sqrt{2\pi}\int_0^{2\pi}d\varphi\int_1^{k_m}dk\int_{-1}^{1}d\mu\frac{k^3}{(k^2+1)^2}\mu \times\left(\mu v_o-\frac{n\omega_o}{k}\right)\exp\left[-\frac{1}{2}\left(\mu v_o-\frac{n\omega_o}{k}\right)^2\right] \times J_n^2\left(\frac{v_Q}{\omega_o}k\mu\cos\alpha+\frac{v_Q}{\omega_o}k\sqrt{1-\mu^2}\sin\alpha\cos\varphi\right)\frac{\sin(kl)}{kl}. \tag{36}$$

As a result of the splitting in collective and individual modes, the functions S_c and χ are also split in the following way: $S_c=S_c^{\mathrm{col}}+S_c^{\mathrm{ind}}$, $\chi=\chi^{\mathrm{col}}+\chi^{\mathrm{ind}}$, where $\chi^{\mathrm{col}}=S_c^{\mathrm{col}}/S_p$ and $\chi^{\mathrm{ind}}=S_c^{\mathrm{ind}}/S_p$. As has been discussed above, when $l=0$

then $\chi=1$. In this case, Eq. (23) shows that $S_c=S_p$. Therefore, to find the collective and individual contributions to the function χ, it is necessary to calculate the function S_c at $l=0$.

V. RESULTS AND DISCUSSIONS

Here we use the general expressions, Eqs. (31)–(36), to make a parametric analysis of the correlation effect combined with the laser-field assistance on the plasma stopping power. The relevant integrals are numerically calculated using the Gauss-Legendre quadrature.

Making the simplifying assumption that the two test particles have the same charge ($Z_1=Z_2=Z$), the expression for the laser-assisted dicluster stopping power, Eq. (24), can be rewritten as

$$S_{2p}=2Z^2 S_p(v_o,\omega_o,\alpha,v_Q)[1+\chi(v_o,\omega_o,\alpha,v_Q,l)]. \tag{37}$$

The second term on the second member of the above expression gives the correlation effects on the laser-assisted plasma stopping power. The first term, which corresponds to the particular case $\chi=0$ $(l\rightarrow\infty)$, gives the laser-assisted plasma stopping power for two uncorrelated charges. The function χ directly measures the intensity of correlation effects on the plasma stopping power.

In experimental situations where the beam and the plasma parameters are known, the laser parameters must be calculated in order to match the restrictions of the model. We give below some useful relations which can be readily used to calculate the parameters needed in the general expressions of the plasma stopping power:

$$\omega_p\ [\text{rad/s}]=5.64\times10^4(n_o\ [\text{cm}^{-3}])^{1/2},$$

$$\lambda_D\ [\text{cm}]=7.34\times10^2\left(\frac{T\ [\text{eV}]}{n_o\ [\text{cm}^{-3}]}\right)^{1/2},$$

$$N_D=(7.43)^3\times10^6\frac{(T\ [\text{eV}])^{3/2}}{(n_o\ [\text{cm}^{-3}])^{1/2}},$$

$$v_t\ [\text{cm/s}]=4.19\times10^7(T\ [\text{eV}])^{1/2}, \tag{38}$$

$$n_c\ [\text{cm}^{-3}]=\frac{10^{21}}{(\lambda_o\ [\mu\text{m}])^2},$$

$$v_Q=6.02\times10^{-7}\left(\frac{I\ [\text{W/cm}^2]\lambda_o^2\ [\mu\text{m}]}{T\ [\text{eV}]}\right)^{1/2},$$

$$v_o=\left(\frac{E\ [\text{eV}]}{T\ [\text{eV}]}\frac{m\ [\text{g}]}{M\ [\text{g}]}\right)^{1/2}.$$

In the above expressions, the quantities without units are dimensionless. The laser intensity is denoted by I, n_c is the plasma critical density, and E is the energy of the test ions or beam ions. The criterium $I\lambda_o^2\geqslant10^{17}$ $(\text{W/cm}^2)\mu\text{m}^2$ is taken from Kruer [27] to define a very high laser intensity; thus, fixing the plasma temperature, the quiver velocity can be used as a direct measure of the laser intensity.

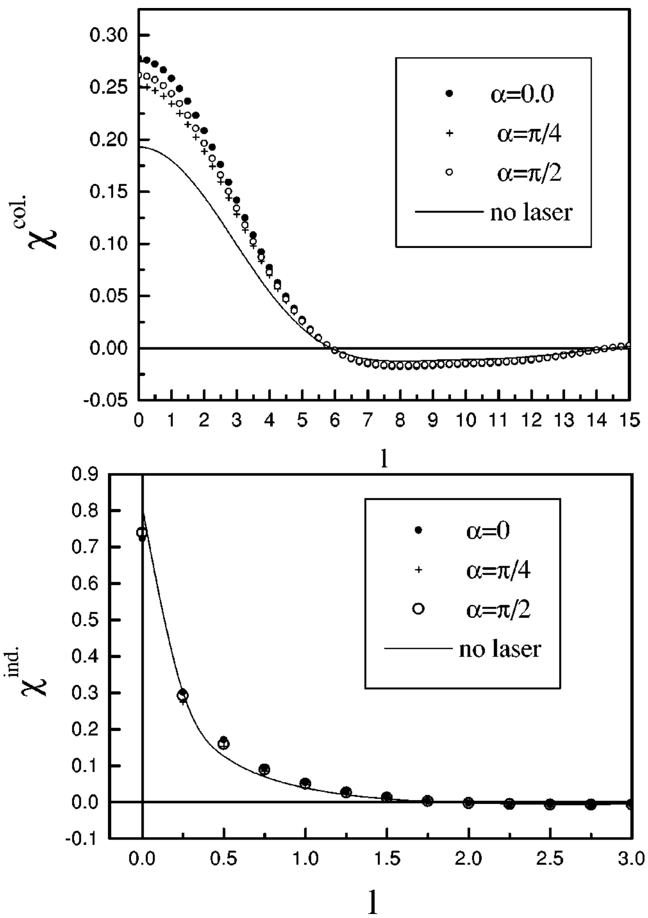

FIG. 1. Collective and individual components of the vicinage function as a function of the interionic distance l for several values of α and for the following fixed parameters: $\omega_o=31$, $v_Q=3.7$, and $v_o=2.87$. All quantities are expressed in normalized variables. See Eq. (12).

To give a practical illustration of the theory developed here, let us use the experimental data reported in Ref. [26]. In that experiment, the authors have used a completely ionized hydrogen plasma, whose temperature and density can take values up to 3 eV and 7.0×10^{16} cm^{-3}, respectively. They also have used a beam of Kr ions with 3.8 MeV of energy and effective charges estimates $Z^{\text{ef}}=3.1, 4.5, 6.4,$ and 7.8, for ionization degrees 90%, 99%, 99.9%, and 100%, respectively. With the help of Eqs. (38), it follows that a CO_2 laser of frequency $\omega_o=1.78\times10^{14}$ rad/s and wavelength $\lambda_o=10.6$ μm is appropriate to use in this application. The plasma critical density is $n_c=8.9\times10^{18}$ cm^{-3}. The values chosen for the plasma density and temperature are, respectively, $n_o=10^{16}$ cm^{-3} and $T=3.0$ eV ; the fixed parameters chosen for the krypton ions are $M=83.8$ g and $Z^{\text{ef}}=4.5$. The ion beam energy can be experimentally varied and its initial value was chosen $E=3.8$ MeV, which implies a test charge velocity $v_o=2.87$.

We use Eq. (37) to calculate the correlation term of the stopping power, expressed by the function χ, and which is not discussed in Ref. [24]. We also calculate the laser effects on the plasma stopping power for a dicluster system which are not included in Refs. [16] and [17]. The results are shown in Figs. 1–5. In all these figures the following dimensionless

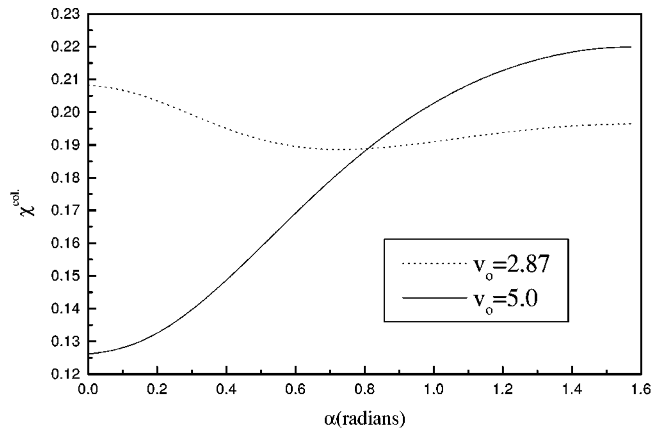

FIG. 2. Collective vicinage function component as a function of the polarization angle α for two different values of the test particle velocity. The fixed parameters are $\omega_o=31$, $v_Q=3.7$, and $l=2.0$.

parameters are kept fixed: $\omega_o=31$, $N_D=7$, and $Z=Z^{\rm ef}/N_D=0.63$.

Figure 1 shows the collective and individual components of χ as a function of the interionic distance l. We have used a laser intensity $I=10^{12}$ W/cm^2 ($I\lambda_o^2\simeq10^{14}$ W μm^2/cm^2) or $v_Q=3.7$, three values of the laser polarization angle α (0, $\pi/4$, and $\pi/2$), and a beam test charge velocity $v_o=2.87$.

Let us initially note some trends of our results that are evident in Fig. 1(a) The asymptotic behavior of χ is verified; $\chi\rightarrow0$ when $l\rightarrow\infty$ and $\chi=1$ for $l=0$. (b) The laser field does not affect at all the individual component $\chi^{\rm ind}$. (c) The individual contribution $\chi^{\rm ind}$ can be neglected for interionic distances $l\gtrsim1.0$, as long the test charge velocity is greater than the thermal velocity; $v_o>1$. The function χ, as in the laser-free case, is a monotonically decreasing function of l in the range $0\lesssim l\lesssim6.0$ but its value is modified by the laser intensity and the polarization angle, as shown by the curves labeled $\alpha=0.0$, $\alpha=\pi/4$, and $\alpha=\pi/2$. All these curves coalesce to the full line labeled ''no laser,'' as the laser intensity goes to zero, and describe the strength of the stopping power correlation term relative to its asymptotic value $2Z^2S_p$.

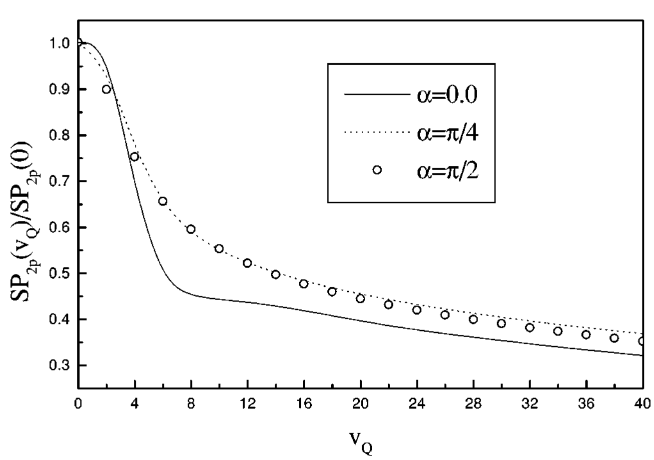

FIG. 3. Relative laser-assisted plasma stopping power as a function of the quiver velocity v_Q (or laser intensity) for three different values of the polarization angle α. The fixed parameters are $\omega_o=31$, $v_o=2.87$, and $l=2.0$.

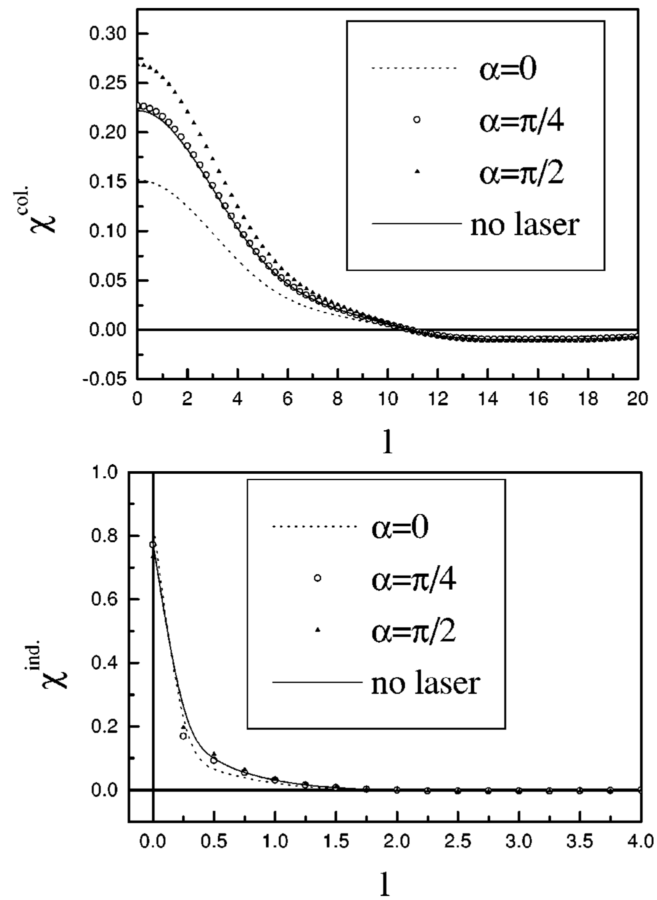

FIG. 4. Collective and individual component of the vicinage function as a function of the interionic distance l for three different values of the polarization angle α. The test charge velocity is higher than in Fig. 1, $v_o=5.0$. Fixed parameters $\omega_o=31$ and $v_Q=3.7$.

Now, for the interionic distance range $l\gtrsim6.0$, the function χ shows no significant difference from the laser-free case. Furthermore, χ practically has reached its asymptotic value ($\chi=0$) and, consequently, the laser-assisted stopping power is correctly described by Ref. [24]. If the laser intensity is in-

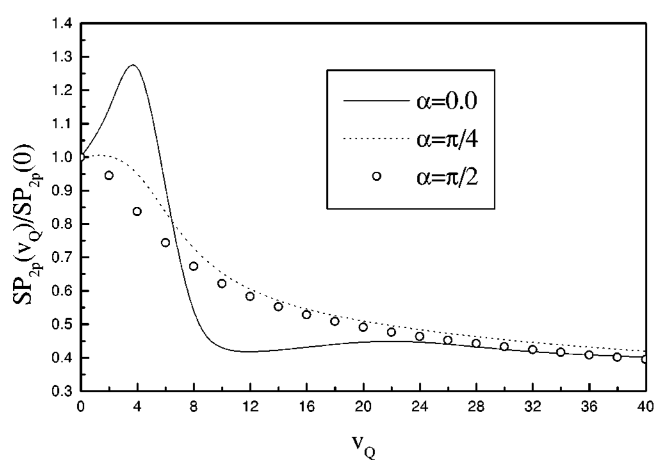

FIG. 5. Relative laser-assisted plasma stopping power as a function of the quiver velocity v_Q (or laser intensity) for three different values of the polarization angle α. The velocity is higher than in Fig. 3, $v_o=5.0$, simulating a higher beam energy of about 12 MeV. Fixed parameters are $\omega_o=31$ and $l=2.0$.

creased, the curves of χ as a function of l keep the same qualitative profile of the ones shown in Fig. 1 but the χ values increase monotonically with the laser intensity.

The variation of the vicinage function with polarization angle is better seen in Fig. 2. We have used an interionic distance $l=2.0$. For values of the test charge velocity v_o smaller than the quiver velocity v_Q, χ varies mildly with the polarization angle, showing a shallow minimum around $\alpha=45°$. This is indicated by the curve corresponding to $v_o=2.87$. For test charge velocities above the quiver velocity, χ starts to increase monotonically with α and presents a broad maximum around $\alpha=\pi/2$. This is indicated by the curve corresponding to $v_o=5.0$.

Figure 3 shows explicitly the effect of the laser field on the plasma stopping power for a dicluster system. The ratio of the stopping power values in the laser-assisted case to its values in the laser-free case is plotted as a function of the quiver velocity (or laser intensity) for the fixed values $\omega_o=31$, $v_o=2.87$, and interionic distance $l=2.0$. The curves labeled $\alpha=0$, $\pi/4$, and $\pi/2$ describe three distinct laser polarization angles. Clearly, for any polarization angle, as the laser-field intensity increases, the plasma stopping power decreases. As an example, for a quiver velocity $v_Q=8.0$, corresponding to a laser intensity $I=4.7\times10^{12}$ W/cm^2, the plasma stopping power decreases about 55% as compared to the laser-free dicluster case. For values of the laser intensity, $v_Q \gtrsim 3.0$, the stopping power is lower when the laser field is polarized along the test charge velocity, i.e., $\alpha=0$.

Let us now investigate the dependence of the stopping power with beam energy. Figure 4 shows the collective and individual components of the vicinage function χ as a function of the interionic distance l for three values of the laser polarization angle: $\alpha=0$, $\alpha=\pi/4$, and $\alpha=\pi/2$. The dicluster velocity is $v_o=5.0$, which is greater than the value in Fig. 1, to simulate a beam energy of about 12 MeV. We note that χ has reached its asymptotic value ($\chi=0$) around $l\simeq11$, so that the range where the correlation is important is broader than in the lower-energy case (Fig. 1). Since the beam density n scales with the interionic distance l as $n\propto l^{-3}$, the correlation term of the stopping power is important even at low beam densities. In contrast with the case of Fig. 1, the laser effect on the correlation function χ is smaller for $\alpha=0$, in agreement with Fig. 2.

Figure 5 shows the relative laser-assisted plasma stopping power as a function of the quiver velocity as in Fig. 3, but for a higher test charge velocity $v_o=5.0$. For polarization angles greater than $\pi/4$, the relative stopping power is a monotonically decreasing function of the quiver velocity. On the other hand, for $\alpha<\pi/4$, it has an oscillatory behavior for small values of the quiver velocity but decreases asymptotically with v_Q as for larger values of the polarization angle.

We conclude from Figs. 3 and 5 that, at a sufficiently high laser intensity, the plasma stopping power decreases very slowly. In practice, this means that there is no need to use very high laser intensities to substantially change the stopping power. We also observe that the polarization angle dependence of the stopping power becomes less important for high intensities. Therefore, for a given beam energy, it is possible to combine the laser polarization angle and the laser intensity to decrease the plasma stopping power. These conclusions may be important for inertial confinement fusion experiments that use high-energy ion beams as drivers, once the beam must deposit its energy as deep as possible inside the target.

Observing our general expressions, Eqs. (31)–(36), we see that the plasma is less effective in stopping the ions for higher velocities. In spite of that, the effects of the laser field upon the plasma properties clearly show up, changing the plasma stopping power in a significant way. This is clearly demonstrated by the results of Fig. 5.

VI. CONCLUDING REMARKS

In this work, using the Vlasov-Poisson model, we discussed the interaction of a beam of charged particles interacting with a completely ionized plasma in a laser field. Starting with the general expressions for two correlated charges, the laser-assisted plasma stopping power is systematically discussed and applied for the low-energy beam plasma experiment reported in Ref. [26].

In numerical calculations, care must be taken in the convergence of the integrals over the laser harmonics and on the high oscillating character of the Bessel and of the trigonometric functions. Typically, for the parameters used in the collective mode, the integrals converge within a relative error of 1%, for 30 laser harmonics.

With the results presented in this work, it is possible to speculate whether a laser field can act as a beam energy regulator in experiments of inertial confinement fusion. For the range of parameters used here, that possibility is clearly feasible. Although in a real inertial confinement fusion experiment the parameters describing the beam plasma interaction impose more restrictive constraints on the model, the same type of calculations carried out in this paper is applicable.

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