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Review article

Review of stopping power and Coulomb explosion for molecular ion in plasmas

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Abstract

We summarize our theoretical studies for stopping power of energetic heavy ion, diatomic molecular ions and small clusters penetrating through plasmas. As a relevant research field for the heavy ion inertial confinement fusion (HICF), we lay the emphasis on the dynamic polarization and correlation effects of the constituent ion within the molecular ion and cluster for stopping power in order to disclose the role of the vicinage effect on the Coulomb explosion and energy deposition of molecules and clusters in plasma. On the other hand, as a promising scheme for ICF, both a strong laser field and an intense ion beam are used to irradiate a plasma target. So the influence of a strong laser field on stopping power is significant. We discussed a large range of laser and plasma parameters on the coulomb explosion and stopping power for correlated-ion cluster and C_{60} cluster. Furthermore, in order to indicate the effects of different cluster types and sizes on the stopping power, a comparison is made for hydrogen and carbon clusters. In addition, the deflection of molecular axis for diatomic molecules during the Coulomb explosion is also given for the cases both in the presence of a laser field and laser free. Finally, a future experimental scheme is put forward to measure molecular ion stopping power in plasmas in Xi’an Jiaotong University of China.

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1. Introduction

Energy loss of ions propagating in plasmas has been a subject of research for several decades because it has lots of applications in many different fields of science such as inertial confinement fusion, plasma diagnostics, and medical applications [1−5]. In particular, interactions of energetic molecular ion or cluster ion beams with matter have attracted a lot of attention due to their good quality in many aspects [6−9]. One of the most obvious advantages that relates to the cluster ion is the effect due to a very low charge to mass ratio. As a result, a cluster ion beam at any given current density can transport up to thousands of times more atoms than a monomer ion beam does at the same current density. This will allow the cluster ion beam to be focused to an extremely small focal spot compared to that in the case of conventional heavy ions. Another advantage of cluster ion beam is that they can transport a large number of low-energy atoms even when the total energy of the accelerated cluster ions is high. However, it is very difficult to realize such a process with conventional monomer ion [8,9]. Driven by the recent developments in the experimental

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accelerator techniques for cluster ion beams [10] and laser technology [11], a promising inertial confinement fusion scheme is proposed [12,13], in which a plasma target is irradiated simultaneously by both an intense ion beam and a laser beam. Such experiments usually can be carried out with the following setup: A thin foil of solid material is irradiated with a laser pulse so it becomes a hot dense plasma. At the same time, an ion beam is sent into the material in the opposite direction. Several experiments [14−17] have been carried out to measure the stopping power and charge variation of heavy ion beams in the laser-ablated plasma targets and warm dense plasma [18]. The experimental results show that the energy loss of projectiles in plasmas is larger than that in cold matter (solid and gases) because of the special properties of the plasma. In the case of plasmas, interactions can happen not only between projectile particles with neutral atoms and bound electrons, but also with ions and free electrons. There are two main reasons to explain enhanced plasma energy loss: one is the increase of projectile charge state due to the reduction of the capture cross sections with target free electrons, and the other is the more efficient energy transfer with free electrons of plasmas.

In theoretical aspects, molecular dynamic simulations are mainly used to study the classical stopping power [19]. The main existing theoretical models include linear and nonlinear Vlasov−Poisson theory [20−25], and the binary collision theory [26]. Besides stopping power, charge state is a prerequisite and another focus of attention [27−29]. For the molecular ions and clusters, several authors have reviewed the development of molecules and clusters propagating in different targets especially in solids [30−33]. However, the interaction of charged molecular ion beam with plasma is still not totally understood. In particular, the experimental data about molecular ions traveling in plasmas are very rare so far. Thus, it is very urgent to carry out the research especially for experiments in this field.

The interaction of an energetic molecule with a plasma target is very different from an individual ion. It can be described by the basic processes as following: In the first stage, the molecule loses the valence electrons in the collisions with plasmas and the molecular structural stability will be broken due to the ionization of its constituent atoms. Subsequently, the ions will lose their energy because they transfer their kinetic energies to the target, at the same time, the repulsion aroused by the dynamically screened Coulomb interaction between the like-charged ions drives them apart and the molecular ion will experience the course of Coulomb explosion. After original break-up of the molecule, its further moving is accompanied by electronic excitations of the target, which show strong interference because of close spatial correlation within the ions, which is known as the vicinage effect. Such an interference aroused by the structure is expected to produce an enhanced stopping power for each ion when compared to the energy loss of a monomer ion traveling at the same speed, as long as the inter-ionic distances within the cluster are smaller than the characteristic length for the electronic excitation. Due to the difference between individual ions, vicinage effect attracts more concerns for molecular ions or cluster slowing down in plasma. Several authors [34−40] have adopted linear Vlasov−Poisson theory to study the energy loss of molecular ions or clusters in plasma targets. However, the Coulomb explosion hasn't been considered in their works. It is well known that, the Coulomb explosion is a very interesting phenomenon for the molecules and clusters propagating in plasmas. It can not only change the shape and structure of clusters, but also influence the stopping power to reach a more transparent information.

On the other hand, driven by the development of experiments, the influence of a high-intensity laser field on the energy loss has been studied by theoretical researchers. As a pioneer, Arista firstly adopted a general formulation based upon a time-dependent Hamiltonian. He described the influences of a strong laser field on the energy loss of an energetic ion traveling in a degenerate electron gas [41]. In the plasma case, the study results were as follows: When the projectile speed was less than the plasma electron thermal speed, the laser field decreased the energy losses [12]. While in the high-intensity limit, projectile particles might be accelerated by the laser field [20]. The influence of the laser field on the energy loss of ion clusters penetrating in hot plasma has been studied by Silva and Galvão [42]. When compared to a laser-free case, the study results showed that the laser field affected the vicinage effect aroused by the spatial correlation among the cluster constituent particles and caused a decrease of the energy loss. Furthermore, the energy loss of ions in plasmas irradiated by an intense laser field was studied by Nersisyan and Deutsch. It was found that the laser field might strongly reduce the mean energy loss for slow ions when increasing it at high speeds [43]. Moreover, Hu et al. adopted a two-dimensional particle-in-cell simulation to study the dynamic polarization and energy loss for an energetic ion beam moving through a two-component plasma, which was simultaneously irradiated by a strong laser pulse [44]. In our works, the energy loss, Coulomb explosion and laser effects for molecular ion and clusters in plasma are considered based on the molecular dynamic (MD) simulation [45−50]. In order to get more clear information about molecular ions and cluster interaction with plasma targets, especially about Coulomb explosion and laser effects, we summarize our recent theoretical studies about molecular ions and clusters propagating through plasma targets. In this review paper, we focus on discussing the influences of laser effects, plasma parameters, vicinage effects and cluster size on Coulomb explosion and stopping power. In particular, a comparison is made for hydrogen clusters and carbon clusters on the stopping power. In addition, considering the scarcity of experimental data about molecular ion propagating in plasma, a future experimental scheme is put forward to measure the stopping power. It will be carried out by our cooperators in Xi'an Jiaotong University in the future.

The paper is organized as follows. In Sec. 2, following the theoretical model, the heavy ion stopping power in plasma is discussed. Then, the interaction potential, stopping power and Coulomb explosion for diatomic molecular hydrogen and C_{20} cluster traveling in plasmas are given. In Sec. 3, a large range of plasma parameters on Coulomb explosion and stopping power and the laser effects on the Coulomb explosion and stopping power of the correlated-ion N_2 and C_{60} cluster are discussed. In Sec. 4, a future experimental scheme is put forward to measure the stopping power for molecular ion moving in plasma. Finally, a brief summary of the results is presented in Sec. 5.

2. Stopping power and Coulomb explosion

Let us consider a fast N-homo-nuclear cluster with the charge number Z_1. We assume the projectile cluster moves at the velocity v in the z direction penetrating through a plasma target with the plasma density n_0 and the electron temperature T. By using the linear Vlasov–Poisson theory and Fourier-like analysis, we can get the expression of interaction potential between the two constituent ions in the cluster

$$U(\boldsymbol{r}_{jl},\boldsymbol{v}) = \frac{1}{2\pi^2}\int \frac{d^3\boldsymbol{k}}{k^2}\frac{\rho_\eta^2(k)}{\varepsilon(k,\boldsymbol{k}\cdot\boldsymbol{v})}e^{i\boldsymbol{k}\cdot\boldsymbol{r}_{jl}}, \tag{1}$$

where the two ions are located at $\boldsymbol{r}_j$ and $\boldsymbol{r}_l$ in the center of mass (CM) frame of the moving molecular ion respectively, $\boldsymbol{r}_{jl} = \boldsymbol{r}_j - \boldsymbol{r}_l$ is the expression of position vector of the jth ion relative to the lth ion, ρ_η is the charge densities of bound-electron for a heavy ion in classical plasma [35]

$$\rho_\eta(k) = Z_1 e\left[1 - \frac{\eta}{1+(k\Lambda)^2}\right], \tag{2}$$

with $\eta = \frac{2}{9}\sqrt{\frac{2}{3\pi}}\frac{\sqrt{Z}}{[1+(v/v_T)^2]^{3/2}}$. The screening length is defined by $\Lambda/\lambda_D = \left(2\pi/27\right)^{1/4} z^{1/4}$, where $z = Z_1/N_D$ with $N_D = n\lambda_D^3$ being the number of plasma particles in a typical Debye volume and $\lambda_D = \sqrt{K_B T/m_e}$, $v_T = \sqrt{K_B T/m_e}$ are the electron Debye screening length and the electron thermal speed respectively.

In the dielectric formalism, the target is characterized by the dielectric function $\varepsilon(k,\omega)$, in which a lot of useful relevant information is contained, such as the response to electronic excitations induced by the charged particle passing through plasmas. For the classical electron plasma, the longitudinal dielectric function is given as

$$\varepsilon(k,\omega) = 1 + (k\lambda_D)^{-2}\left[X(\omega/kv_T) - (k\lambda_D)^2 + iY(\omega/kv_T)\right]. \tag{3}$$

During the penetration through a plasma target, a molecular ion dissociates into a cluster composed of N ions. Invoking the assumption of the adiabatic change for the inter-ionic distances during the penetration through the target, the Coulomb explosion patterns can be described by solving the equations of motion for the individual ions within the cluster. Thus, the motion of the jth ion in the cluster's CM frame of reference can be written as

$$m\frac{d^2\boldsymbol{r}_j}{dt^2} = \boldsymbol{F}_j^s(\boldsymbol{v}) + \sum_{j\neq l=1}^{N}\boldsymbol{F}(\boldsymbol{r}_{jl},\boldsymbol{v}), \tag{4}$$

where m is the ion mass. By using the interaction potential, we can get the self-stopping forces and the interaction forces as follows

$$\boldsymbol{F}_j^s(\boldsymbol{v}) = -\partial U(\boldsymbol{r}_{jl},\boldsymbol{v})/\partial\boldsymbol{r}_{jl}\big|_{\boldsymbol{r}_{jl}=0} \tag{5}$$

$$\boldsymbol{F}_j^s(\boldsymbol{r}_{jl},\boldsymbol{v}) = -\partial U(\boldsymbol{r}_{jl},\boldsymbol{v})/\partial\boldsymbol{r}_{jl}, j\neq l \tag{6}$$

Assuming the cluster moves in the z direction, one can divide the total cluster stopping power into two parts

$$S_{cl}(v,t) = S_0(v) + S_v(v,t), \tag{7}$$

where $S_0(v) = -\sum_{j=1}^{N}F_j^s(v)$ is the contribution from the individual self-stopping forces, $S_v(v,t) = -\sum_{j=1}^{N}\sum_{j\neq l=1}^{N}(\boldsymbol{F}_{jl})_z(\boldsymbol{r}_{jl},\boldsymbol{v})$ is the vicinage stopping power which describes the interferences in the stopping power caused by the spatial correlation within the constituent ions.

For the sake of clarifying the role of Coulomb explosions in the vicinage effect on the molecular energy loss, the stopping power ratio, $R = 1 + S_v(x,z,v)/NS_{Z_1}(v)$, is introduced as a function of the penetration time.

2.1. Molecular interaction potential

Based on the theoretical model, we will give the dependence of the potential on the projectile speeds. In Fig. 1, one can see that the variation of the total interaction potential U with the longitudinal distance z for a two-ion cluster traveling with different velocities v through a plasma target. The plasma parameters $n_0 = 10^{20}$ cm^{-3}, $T = 10^2$ eV, and the given radial distance $\rho = \lambda_D$. The results show that the variation of the potential on the coordinate z is rather asymmetric, as a result of the wake-like oscillatory spatial pattern caused by the medium response.

For the sake of revealing the characteristics of the wake effects more clearly, we further plot the dependence of the polarization potential on both ρ/λ_D and z/λ_D for a projectile velocity $v = 2v_T$ in Fig. 2(a) and (b) with the same parameter set as in Fig. 1.

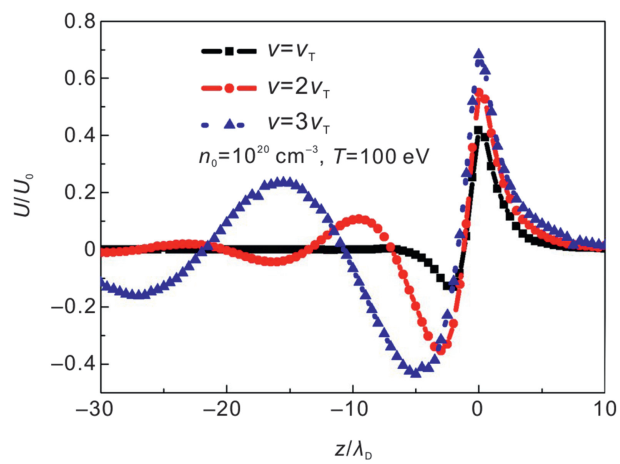

Fig. 1. Total interaction potential U as a function of the coordinate z/λ_D for a two-ion cluster with different speeds $v = v_T, 2v_T$, and $3v_T$, moving at the transversal distance $\rho = \lambda_D$ through a plasma with $n_0 = 10^{20}$ cm^{-3} and $T = 10^2$ eV. Here, $U_0 = (Z_1 e)^2/\lambda_D$.

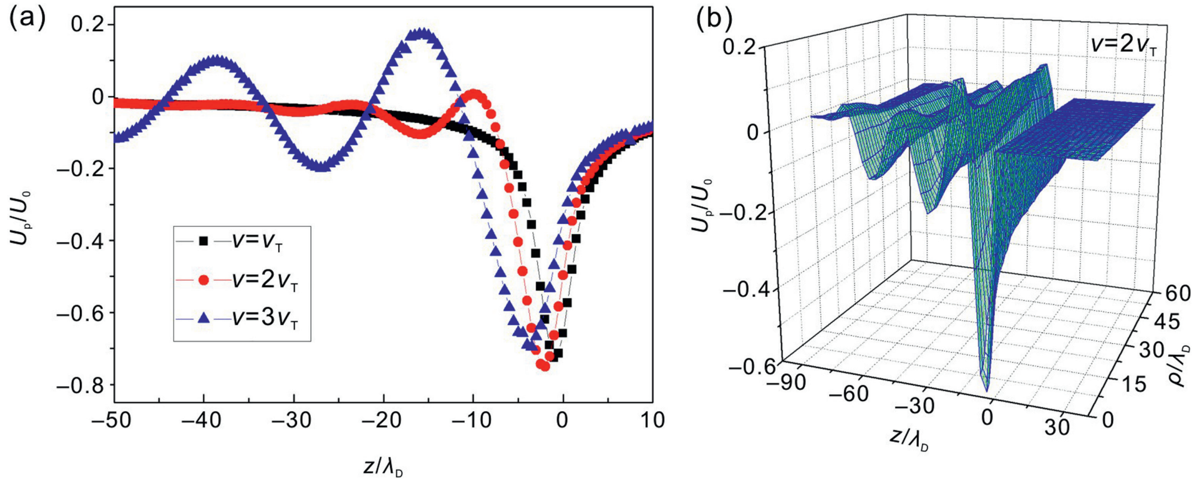

Fig. 2. (a) Polarization potential U_p as a function of the longitudinal distance z/λ_D and (b) U_p as a function of z/λ_D and the transversal distance ρ/λ_D for a two-ion cluster with velocity $v = 2v_T$, traveling through a plasma with the same parameters as in Fig. 1.

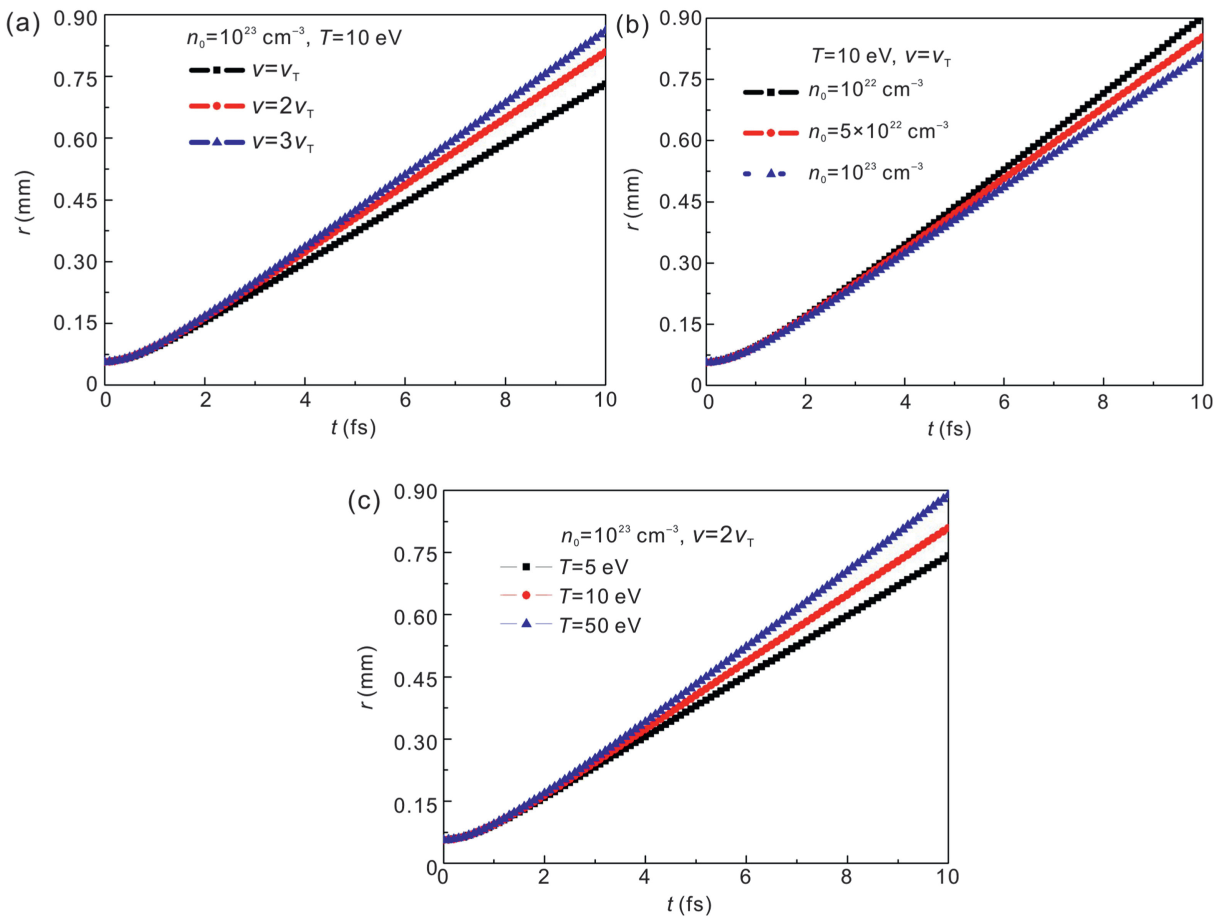

Fig. 3. The internuclear distance r as a function of the penetration time t during the Coulomb explosion of a hydrogen molecular ion with initial angle $\theta_0 = 60°$, traveling through plasmas with (a) different velocities $v = v_T$, $2v_T$, and $3v_T$, and given the plasma density as $n_0 = 10^{23}$ cm^{-3} and temperature $T = 10$ eV; (b) different plasma densities $n_0 = 10^{22}$ cm^{-3}, 5×10^{22} cm^{-3}, and 10^{23} cm^{-3}, and plasma temperature $T = 10$ eV and velocity $v = v_T$; (c) different electron temperatures $T = 5$, 10 and 50 eV, and plasma density $n_0 = 10^{23}$ cm^{-3} and velocity $v = 2v_T$.

2.2. Diatomic molecular cluster

If we take H_2^+ as an example, we can get $Z_1 = 1$, $N = 2$, and $\rho_\eta(k) = Z_1 e$. Fig. 3(a)−(c) show the influences of the variations of (a) the projectile velocity, $v = v_T$, $2v_T$, and $3v_T$, (b) the plasma density, $n_0 = 10^{22}$ cm^{-3}, 5×10^{22} cm^{-3}, and 10^{23} cm^{-3}, and (c) the electron temperature, $T = 5$, 10 and 50 eV, on the dependence of the penetration time, during

Coulomb explosions of H_2^+ with a standard set of parameters: $v = 2v_T$, $n_0 = 10^{23}$ cm^{-3}, and $T = 10$ eV. It can be seen that the Coulomb explosion will proceed faster for higher velocities, lower plasma densities, and higher electron temperatures.

In order to further clarify the wake effect, we plot Fig. 4(a)–(c) to show the angle between the molecular axis and the beam direction as a function of the penetration time for the same set of parameters in Fig. 3(a)–(c). It can be seen that the molecular axis aligns itself along the beam direction during the course of Coulomb explosion due to the asymmetry of the interaction potential. Generally speaking, tilting of the axis in the direction of motion is stronger in much denser and colder plasmas, that is, for shorter Debye lengths.

Fig. 5(a)–(c) show the stopping power ratio, R, as a function of the penetration time for a H_2^+ moving through a plasma target with the same parameters as those used in Fig. 3(a)–(c).

The numerical results show that, at the beginning of Coulomb explosion, the two constituent ions in the cluster behave as if they are almost united into a single point like projectile with the double charge because as they are so close to each other, the energy loss of the molecular is significantly enhanced compared to the energy loss of the two independently isolated protons. Such an enhancement is greater for faster projectile velocities, lower plasma densities, and higher plasma electron temperatures, respectively. In addition, for longer penetration times t, the stopping ratio R approaches 1, indicating that the two ions have ran apart from each other in Coulomb explosion to sufficiently big separations, so that they act as two completely isolated or uncorrelated perturbers of the plasma.

2.3. C_{20} cluster

For the sake of disclosing the vicinage effects in larger clusters, we focus our study on C_{20} cluster. Fig. 6 gives the three-dimensional coulomb explosion patterns for a C_{20} cluster moving through a plasma target with $T = 1$ eV and $n_0 = 10^{22}$ cm^{-3}. These snapshots of the ion positions are in the cluster CM frame at the penetration time $t = 0$, 5, 15, and 25 fs, respectively, and the fixed projectile speed $v = 3v_T$. It is worthy mentioning that the C_{20} cluster structure turns into an interesting basket-like shape. As a direct consequence of the asymmetry of the wake effect, the inter-ionic forces cause the increasing elongation in the direction of motion for the cluster with the increasing time.

Fig. 7(a)–(c) show the influence of the cluster speeds, plasma temperatures and densities on the Coulomb explosion patterns after 25 fs in a plasma target. It can also be seen that the Coulomb explosion course will proceed faster for higher

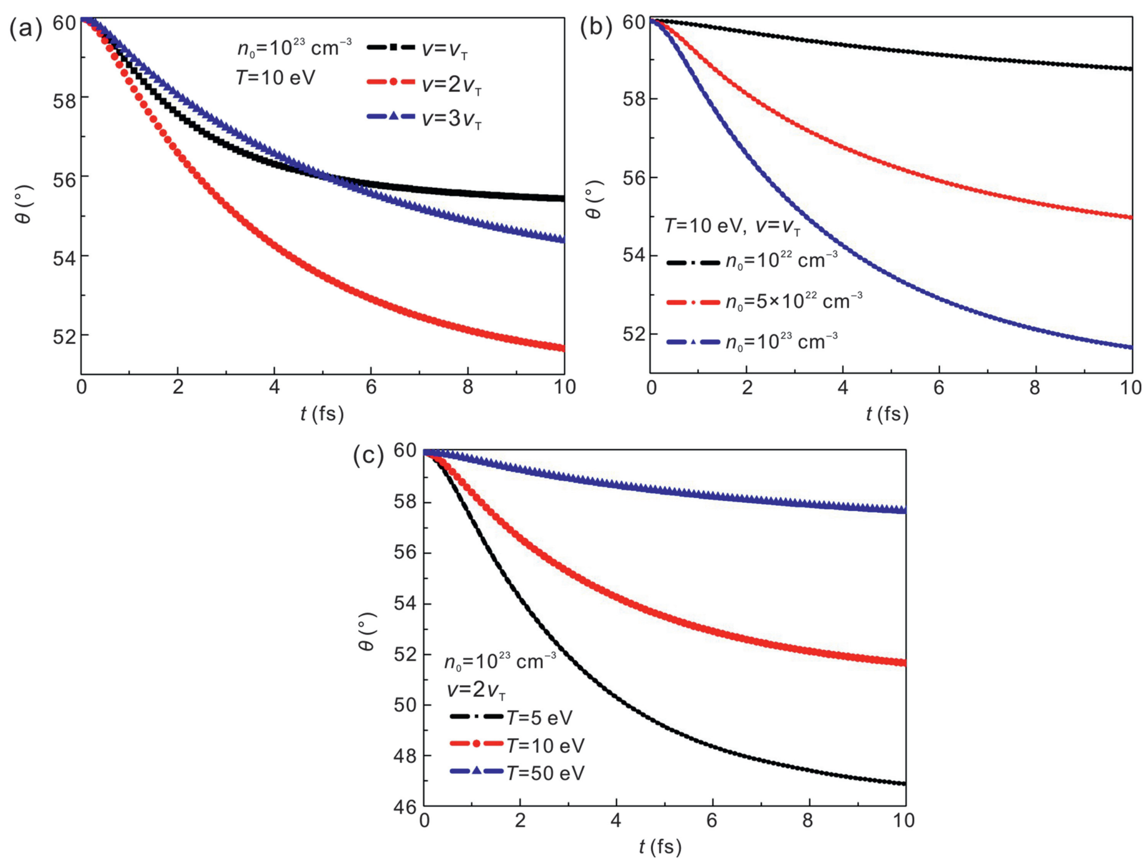

Fig. 4. The angle θ between the molecular axis and the beam direction as a function of the penetration time t during the Coulomb explosion of a hydrogen molecular ion with the initial angle $\theta_0 = 60°$, penetrating through plasmas, with the same set of parameters as those used in Fig. 3(a)–(c).

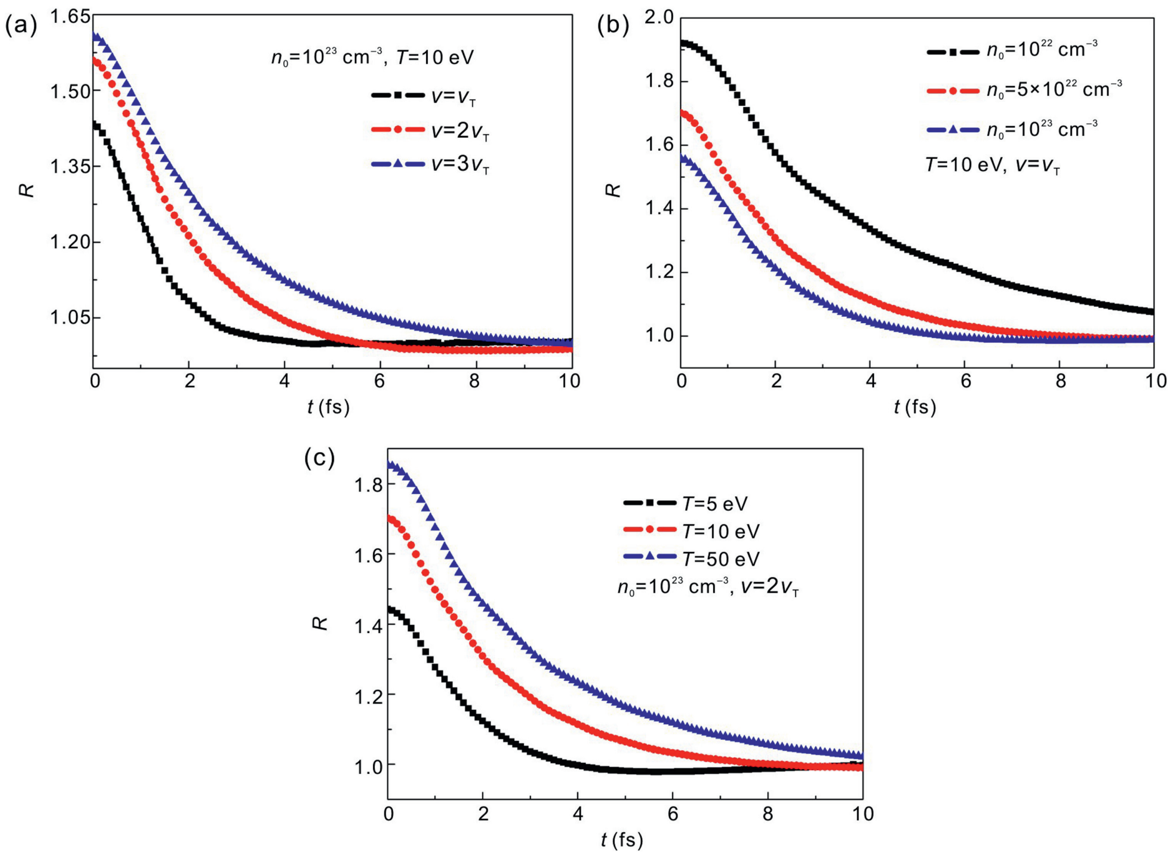

Fig. 5. Stopping power ratio R as a function of the traveling time t during the course of Coulomb explosion for a hydrogen molecular ion with given initial angle $\theta_0 = 60°$, penetrating through plasmas, with the same parameters as those used in Fig. 3(a)−(c).

projectile velocities, lower plasma densities and higher electron temperatures.

In order to show the influences of different cluster type and size on the stopping power, we draw the stopping power ratio R for H_2, C_{20} and C_{60} respectively in Fig. 8. The given parameters $v = 3v_T$, $n_0 = 10^{22}$ cm^{-3} and $T = 2$ eV. Numerical results indicate that the stopping power ratio reaches the highest value for C_{60}. It shows that the stopping power has higher values for much larger and heavier clusters.

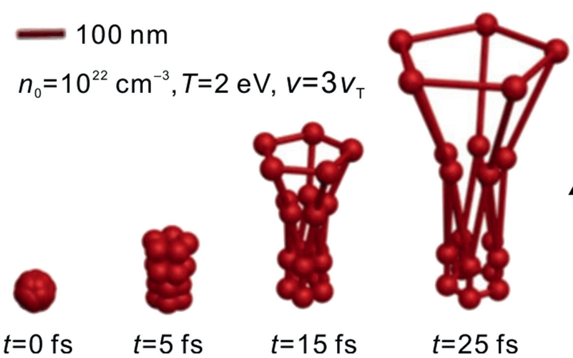

Fig. 6. Three-dimensional coulomb explosion patterns for a C_{20} cluster ion penetrating through plasmas in the indicated direction. Snapshots of several ion positions are shown in a moving frame of reference attached to the cluster, for penetration times $t = 0$, 5, 15 and 25 fs. The plasma density $n_0 = 10^{22}$ cm^{-3} and electron temperature $T = 2$ eV, and the velocity $v = 3v_T$.

3. Laser effects

Under the radiation of the laser field $E_0(\mathrm{t}) = E_0 \sin\omega_0 t$, the scalar potential of a fast N-homo-nuclear ion cluster $U(r,t)$ can be determined by the linearized Vlasov−Poisson equations by using Fourier-like transform in space-time domain and after taking the time average over the laser period. As a result, the average interaction potential between the two constituent ions located at $\boldsymbol{r}_j$ and $\boldsymbol{r}_l$ is

$$U(\boldsymbol{r}_{jl}) = \frac{1}{2\pi^2} \sum_{n=-\infty}^{\infty} \int \frac{\mathrm{d}^3 k}{k^2} \rho_\eta^2(k) \mathrm{J}_n^2(\boldsymbol{k} \cdot \boldsymbol{a}_\mathrm{E}) \frac{\mathrm{e}^{\mathrm{i}\boldsymbol{k} \cdot \boldsymbol{r}_{jl}}}{\varepsilon(k, \omega_n)}, \tag{8}$$

where $\mathrm{J}_n(x)$ is the nth-order Bessel function of the first kind. $\boldsymbol{a}_\mathrm{E} = e\boldsymbol{E}_0/(m_\mathrm{e}\omega_0^2)$ is the transverse oscillation amplitude of electrons, which is driven by the radiation field (the so-called quiver amplitude). $\varepsilon(k,\omega)$ is the longitudinal dielectric function of the classical electron plasma.

For the sake of simplifying the following calculations, the three vectors $\boldsymbol{E}_0$,$\boldsymbol{v}$ and $\boldsymbol{k}$, are assumed to be all in the same plane. We take α to be the angle between $\boldsymbol{E}_0$ and $\boldsymbol{v}$. By introducing variable $\omega = \boldsymbol{k} \cdot \boldsymbol{v} = kv \cos\theta$, we define the quality

$$\chi(k, \omega) = \boldsymbol{k} \cdot \boldsymbol{a}_\mathrm{E} = \frac{a_\mathrm{E}\omega}{v} \cos\alpha - ka_\mathrm{E} \sin\alpha, \tag{9}$$

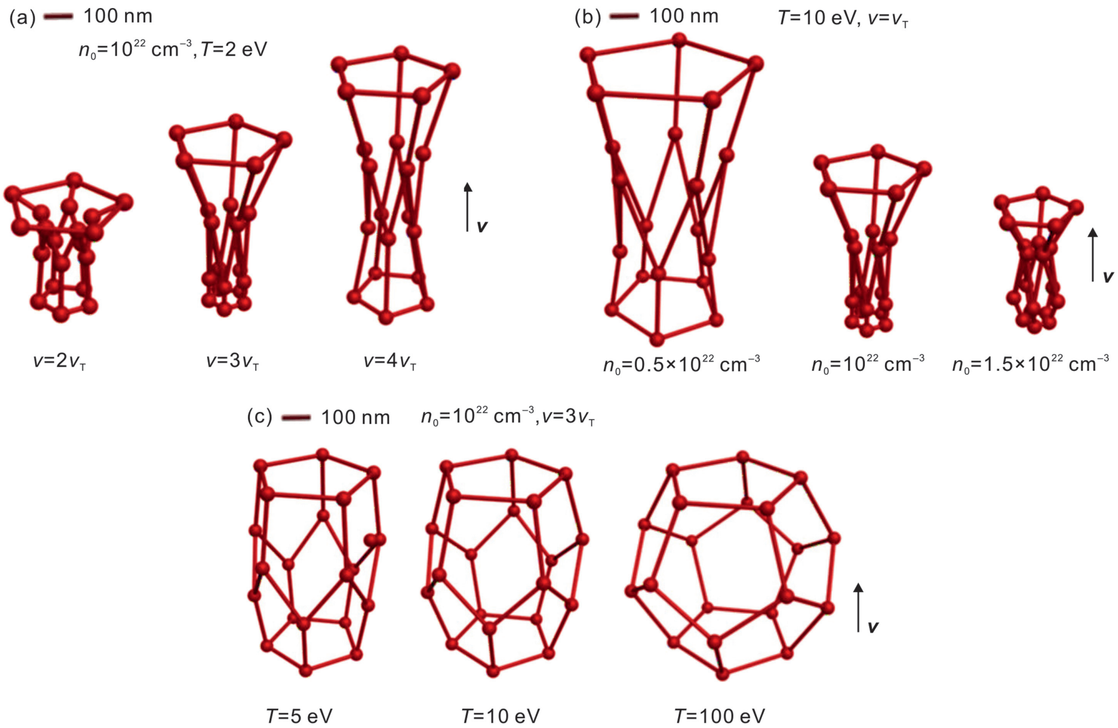

Fig. 7. Influence of (a) different velocities $v = 2v_T$, $3v_T$ and $4v_T$, given plasma density $n_0 = 10^{22}$ cm^{-3} and plasma temperature $T = 2$ eV; (b) different plasma densities $n_0 = 0.5 \times 10^{22}$ cm^{-3}, 10^{22} cm^{-3}, and 1.5×10^{22} cm^{-3}, given electron temperature $T = 10$ eV and projectile speed $v = v_T$; (c) different plasma temperatures $T = 5$, 10 and 100 eV, given plasma density $n_0 = 10^{22}$ cm^{-3} and projectile speed $v = 3v_T$ on the Coulomb explosion patterns after 25 fs for C_{20} penetrating through a plasma target.

where $\kappa = \sqrt{k^2 - \omega^2/v^2}$. Assuming that the velocity is directed along the z-axis in the cylindrical coordinates, the interaction potential can be written as

$$U(\rho_{jl}, z_{jl}) = \frac{2}{\pi v} \sum_{n=-\infty}^{\infty} \int_0^{k_{max}} \frac{dk}{k} \int_0^{kv} d\omega \rho_0^2(k) J_0(\rho_{jl}, k) \times J_n^2[\chi(\kappa,\omega)] \times \left\{ \cos\left(\frac{\omega z_{jl}}{v}\right) \mathrm{Re}\left[\frac{1}{\varepsilon(k,\omega)}\right] - \sin\left(\frac{\omega z_{jl}}{v}\right) \mathrm{Im}\left[\frac{1}{\varepsilon(k,\omega)}\right] \right\}, \quad (10)$$

where $r_{jl} = \sqrt{\rho_{jl}^2 + z_{jl}^2}$. In Eq. (10), we have induced a cut-off wave number $k_{max} = m_e(v^2 + 2v_T^2)/(Z_1 e)^2$ to avoid the divergence of the integral due to incorrect treatment of the short-range interactions between the projectile and electrons in the plasma. In fact, the integral is fast convergent as increasing the values of the upper limit k_{max} if the internuclear distance r holds a limited value.

In the next discussions, the vacuum wavelength λ_0 of the laser field is bigger than the Debye screening length λ_D and the electron oscillation amplitude a_E. Therefore, the laser field should satisfy the following constraints

$$\frac{\omega_0}{\omega_p} < \frac{2\pi c}{v_T} \quad (11)$$

and

$$I < \frac{1}{2} n_0 c (m_e c^2) \left(\frac{\omega_0}{\omega_p}\right)^2, \quad (12)$$

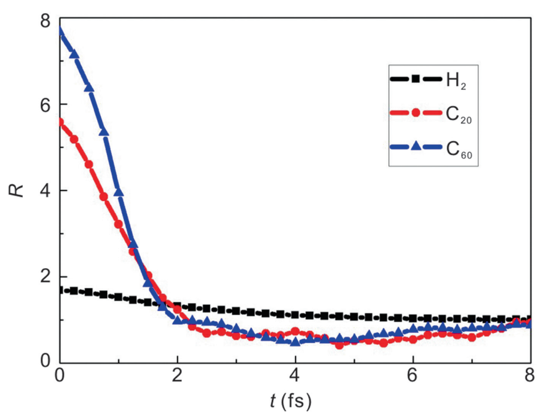

Fig. 8. Stopping power ratio R as a function of the penetration time t during the Coulomb explosion for H_2, C_{20} and C_{60} clusters traveling through a plasma target with given plasma density $n_0 = 10^{22}$ cm^{-3}, electron temperature $T = 2$ eV and speed $v = 3v_T$.

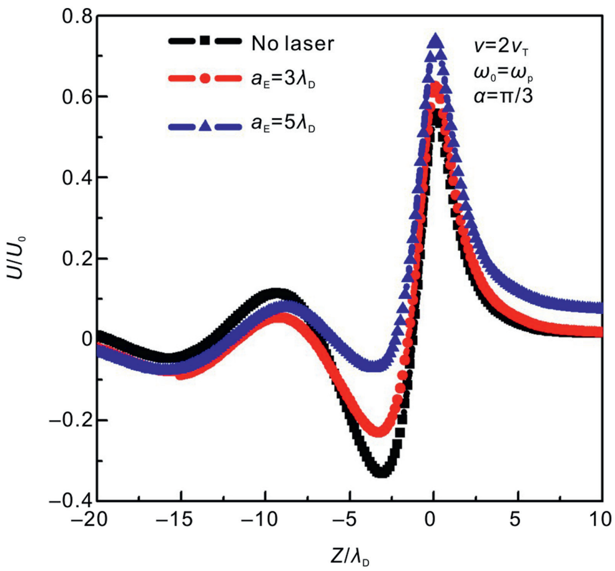

Fig. 9. Influence of the laser intensity (i.e., the quiver amplitude) $\boldsymbol{a}_E = e\boldsymbol{E}_0/(m_e\omega_0^2)$ on the interaction potential U as a function of the longitudinal distance z/λ_D, for a nitrogen ion-cluster at the transversal distance $\rho = \lambda_D$, through a plasma with $n_0 = 10^{16}$ cm^{-3} and $T = 10$ eV. Here, $U_0=(Z_1e)^2/\lambda_D$.

where $I = cE_0^2/8\pi$ is the intensity of the laser field and $\omega_p = \sqrt{4\pi n_0e^2/m_e}$ is the plasma frequency. The plasma critical density n_c can be estimated by using the above conditions when the frequency and intensity of the laser field are given.

3.1. Correlated-ion cluster

In order to indicate the effects of laser parameters on the interaction potential, Coulomb explosion and stopping power, we take correlated-ion cluster N_2 as an example.

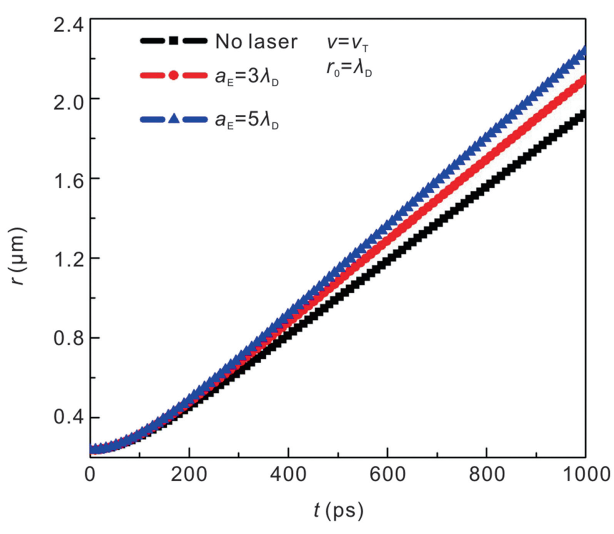

Fig. 10. The interionic distance r as a function of the penetration time t for a nitrogen ion cluster traveling through a plasma target for different laser intensities. Here, the plasma density is $n_0 = 10^{16}$ cm^{-3}, the electron temperature $T = 10$ eV, the initial angle $\theta_0 = 60°$, and the laser parameters $\omega_0 = \omega_p$, $\alpha = \pi/3$.

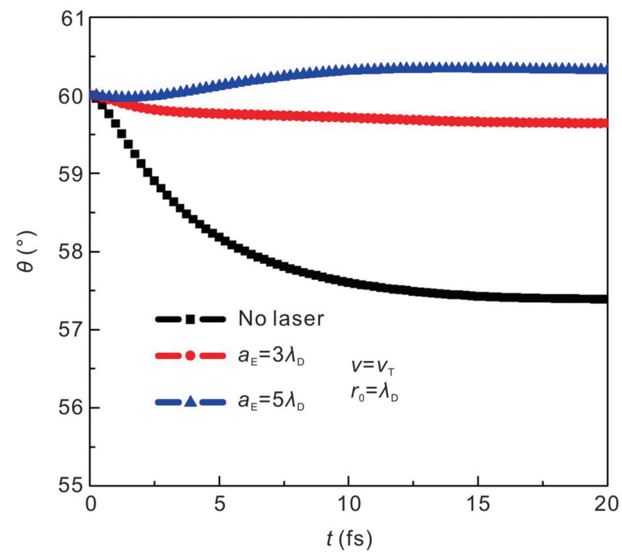

Fig. 11. The laser angle θ as a function of the penetration time t for different laser intensities with the same parameters as those used in Fig. 10.

Figs. 9−12 show the influence of several laser intensities on the interaction potential U, interionic distance r, stopping power ratio R and angle θ between the molecular axis and the beam direction. One can see that the laser-field intensity is a significant factor which can affect the interaction within the ions. The amplitude of oscillations of the polarization potential will cut down. Moreover, the laser-field parameters make the increase of the interionic distance quickened during the course of Coulomb explosion. On the other hand, the molecular axis tends to align itself along the direction of the beam during the Coulomb explosion because of asymmetry caused by the wake effects with increasing penetration time. However, this tendency is significantly reduced by increasing the laser-field intensity. In particular, the direction of the molecular axis will align itself apart from the beam direction for large quiver amplitudes, such as $a_E = 5\lambda_D$.

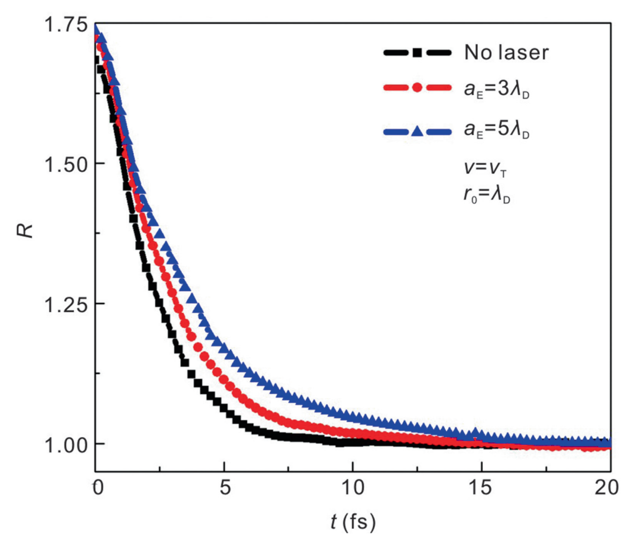

Fig. 12. The stopping power ratio R as a function of the penetration time t for different laser intensities with the same parameters as those used in Fig. 10.

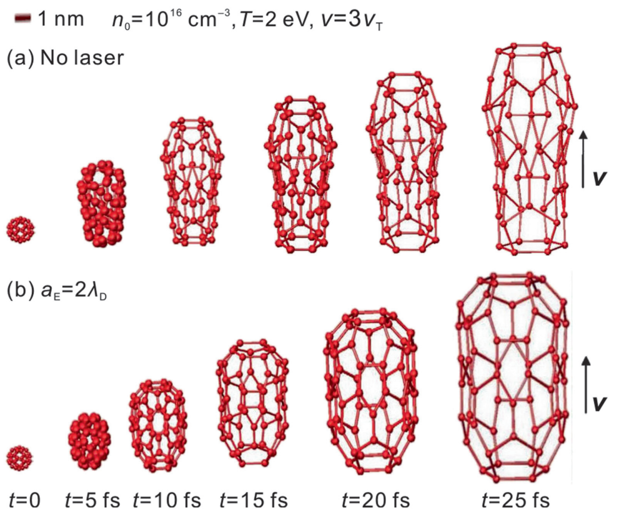

Fig. 13. 3D Coulomb explosion patterns of C_{60} penetrating through a plasma target with density $n_0 = 10^{16}$ cm^{-3} and electron temperature $T = 2$ eV at the velocity $v = 3v_T$ in the indicated direction for (a) no laser and (b) $a_E = 2\lambda_D$ and $\alpha = \pi/3$, respectively. Snapshots of ion positions are shown in a moving frame of reference attached to the cluster, for several penetration time: $t = 0$, 5, 10, 15, 20 and 25 fs.

3.2. C_{60} cluster

Finally, we study the larger cluster C_{60}. Fig. 13 shows the 3D coulomb explosion pattern of a C_{60} cluster penetrating through a plasma target for several snapshots of the ion positions in the cluster CM frame at the penetration time $t = 0$, 5, 10, 15, 20 and 25 fs, respectively. Other parameters are $T = 2$ eV, $n_0 = 10^{16}$ cm^{-3}, and $v = 3v_T$ for (a) no laser and (b) $a_E = 2\lambda_D$ and $\alpha = \pi/3$. The numerical results show an interesting picture that the C_{60} cluster structure turns into a basket-like shape as a direct consequence of the wake-potential asymmetry in the inter-ionic forces. In particular, the cluster becomes increasingly elongated along the direction of motion with increasing time. In contrast to no-laser case, one can see that the laser field weakens the wake effect.

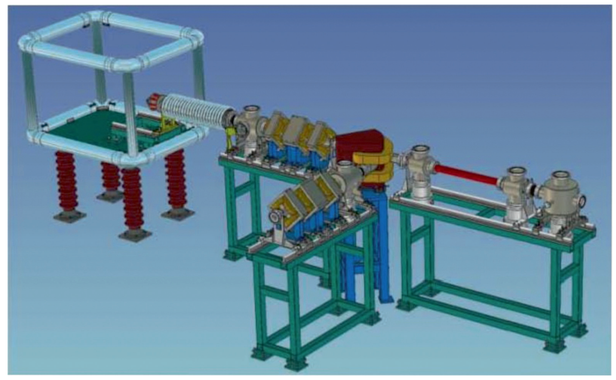

Fig. 15. Experimental platform for the study of (molecular) ion stopping in plasmas under construction in Xi'an Jiaotong University.

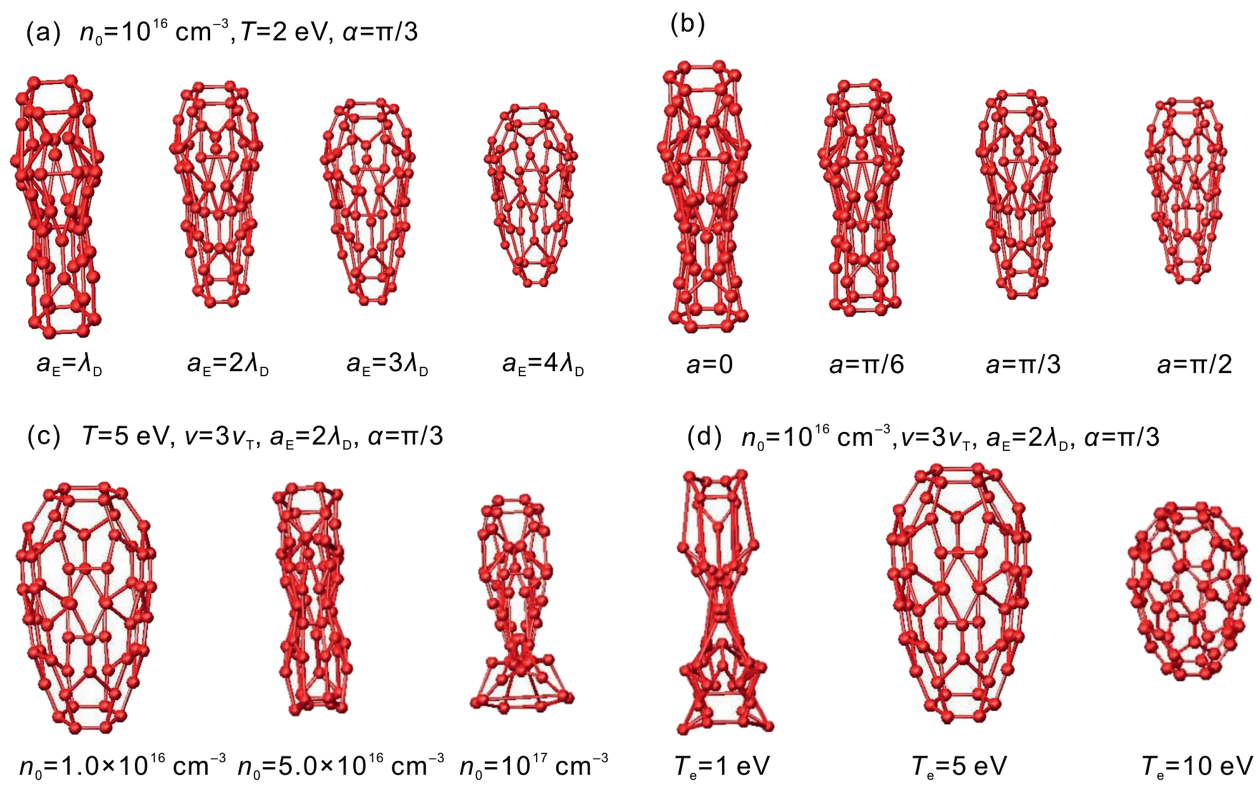

Fig. 14. Influence of (a) different laser intensities, $a_E = \lambda_D$, $2\lambda_D$, $3\lambda_D$, $4\lambda_D$, and fixed parameters $n_0 = 10^{16}$ cm^{-3}, $T = 2$ eV and $\alpha = \pi/3$; (b) different laser angles $\alpha = 0$, $\pi/6$, $\pi/3$, $\pi/2$; (c) different plasma densities $n_0 = 10^{16}$ cm^{-3}, 5×10^{16} cm^{-3}, 10^{17} cm^{-3}, and fixed parameters $T = 5$ eV, $v = 3v_T$, $a_E = 2\lambda_D$ and $\alpha = \pi/3$; (d) different electron temperatures $T = 1$, 5 and 10 eV, and fixed parameters $n_0 = 10^{16}$ cm^{-3}, $v = 3v_T$, $a_E = 2\lambda_D$ and $\alpha = \pi/3$ on the Coulomb explosion patterns after 25 fs for C_{60} cluster moving through a plasma target.

In order to investigate further the influence of laser and plasma parameters on Coulomb explosion, we plot Fig. 14 to show the influence of the effect of different (a) laser intensities $a_E = \lambda_D, 2\lambda_D, 3\lambda_D, 4\lambda_D$, (b) laser angles $\alpha = 0, \pi/6, \pi/3, \pi/2$, (c) plasma densities $n_0 = 10^{16}, 5 \times 10^{16}, 10^{17}$ cm^{-3} and (d) plasma temperatures $T = 1$, 5 and 10 eV on the Coulomb explosion patterns after 25 fs for a C_{60} cluster entering a plasma target. One can see that the Coulomb explosion proceeds slower in the longitudinal expansion along with increasing laser intensity. Meanwhile, the C_{60} cluster asymmetric structure becomes unobvious as the projectile penetration depth increases, which tells that the wake effect is weakened for higher laser intensities.

4. Molecular stopping experimental scheme

Recently, the construction of an experimental platform for the study of molecular stopping in plasmas was started at Xi'an Jiaotong University. As shown in Fig. 15, low charge state ions or molecular ions will be extracted and accelerated from an RF ion source, and then interacted with a plasma or gas. The energy, charge state and mass of the ions after passing though the plasma will be measured by a position sensitive detector behind a deflector. Test experiments are expected to be carried out in the end of 2017.

5. Summary

Based on the linearized Vlasov−Poisson theory, we have reviewed the Coulomb explosion and stopping power of fast molecular ions and clusters in plasmas. For the laser free case, we discussed H_2 clusters and C_{20} clusters. In the presence of a strong laser field, we summarized the correlated nitrogen clusters and C_{60} clusters. We discussed a large range of laser parameters and plasma parameters, which affect the interaction potential, the angle between the diatomic molecular axis and beam direction, Coulomb explosion and stopping power of the clusters. In particular, we have focused on the laser-field effects including the laser-field intensity and laser angle on the dynamically screened interionic interaction governing the Coulomb explosion of the cluster which, in turn, is responsible for weakening the vicinage effects on the molecular stopping power with increasing penetration time through the target. Then, we made a comparison for hydrogen clusters and carbon clusters for the sake of revealing the influences of different cluster sizes on the stopping power. As a result, the stopping power ratio reaches much higher values for much larger and heavier clusters.

In general, correlations among the cluster affect the Coulomb explosion and stopping power of the cluster. Wake effects lead to the diatomic molecular axis to align itself along the beam direction. On the other hand, laser field plays an important role during the interaction between cluster ions and plasmas. Numerical simulations show that the laser-field intensity weakens the wake effects and affects the Coulomb explosion and stopping power of the clusters. Such conclusions may prove helpful in future designs for the use of cluster ion beams to drive inertial confinement fusion and in other applications.

Conflict of interest

The authors declare that there is no conflicts of interest.

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