

LASER ACCELERATION OF NEGATIVE IONS BY COULOMB IMPLOSION MECHANISM

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Abstract

Laser acceleration of negative ions from laser-plasmas via Coulomb implosion mechanism is investigated. When cluster targets or underdense plasmas are irradiated by intense laser pulses, positive ions are accelerated inside the clusters or self-focusing channel via Coulomb explosion mechanism. The electric field induced by the remaining electrons and positive ions accelerates negative ions in the opposite direction. The maximum energy of negative ions is several times lower than that of positive ions. We present the theoretical description and Particle-in-Cell simulation results of the Coulomb implosion mechanism, and show the evidence of the negative ion acceleration in the experiments on the high intensity laser pulse interaction with the cluster targets.

laser light blows away the electrons, the repelling force of an uncompensated electric charge of positive ions causes the cluster Coulomb explosion. In the case of a multi-species cluster with a relatively small number of the negative ions, the electric field formed by the positively charged component accelerates the negative ions inward. The negative ions leave the target after passing through the center or bouncing its vicinity. We mention that possible mechanisms of negative ion creation are discussed in Ref. [13]. Below we formulate the theoretical description and present the results of the Particle-in-Cell (PIC) simulation of the Coulomb explosion/implosion of a multi-species cluster. The evidence of the negative ion acceleration in the experiments on the high intensity laser pulse interaction with the cluster targets is presented as well.

INTRODUCTION

Recent developments in the ultra-intense laser pulse technology resulted in the intensity at the level above 10^{22} W/cm² [1]. The ultra-intense laser pulse interaction with matter opens such new research fields as the fast ignition of inertial thermonuclear fusion [2], the charged particle beam acceleration for medical applications [3], and the development of compact sources of high energy electrons, ions and photons [4, 5, 6] (see also the review article [7] and literature quoted in).

The negative ion generation has attracted a great deal of attention due to various applications as the beam injectors for magnetically confined fusion devices [8], as the heavy ion fusion drivers [9], and for utilizing them in large scale ion accelerators [10]. Negatively charged ion beams are typically generated via the charge exchange process during the positive ion propagation through the alkali metal vapor. However, since the charge exchange cross section rapidly decreases as the incident energy exceeds keV level, it has been an important issue to find an effective way to generate the high energy negative ions. Laser plasma provides a source of the negative ions with the energy in eV~MeV [11, 12]. In the experiment presented in Ref. [11], the negative ions with the energy about MeV have been observed when the water droplets are irradiated by the ultra-short and ultra-intense laser pulse (40 fs, $I \sim 10^{19}$ W/cm²).

In this paper, we discuss the Coulomb implosion mechanism which could explain the acceleration of negative ions. When a cluster target is irradiated by an intense laser pulse and the ponderomotive pressure of the

COULOMB IMPLOSION MODEL

The acceleration of negative ions from laser-plasma is explained by the Coulomb implosion mechanism [14]. We consider the dynamics of the Coulomb explosion for multi-species cloud of ions. The cloud comprises positive and small amount of negative ions. The motions of positive and negative ion components are governed by the hydrodynamics equations and the Poisson equation for the electric field:

$$\partial_t n_{\pm} + \nabla \cdot (n_{\pm} \mathbf{v}_{\pm}) = 0, \quad (1)$$

$$\partial_t \mathbf{v}_{\pm} + (\mathbf{v}_{\pm} \cdot \nabla) \mathbf{v}_{\pm} = \pm e_{\pm} \mathbf{E} / M_{\pm}, \quad (2)$$

$$\nabla \cdot \mathbf{E} = 4\pi \sum (\pm e_{\pm} n_{\pm}). \quad (3)$$

Here, the subscript (\pm) stands for positive and negative ions. \mathbf{E} is the electric field, and n_{\pm} , \mathbf{v}_{\pm} , $\pm e_{\pm}$, and M_{\pm} are ion density, velocity, electric charge and mass, respectively. These equations admit a self-similar solution with homogeneous deformation, for which the densities are homogeneous, $n_{\pm} = n_{\pm}(t)$, and the velocities and electric field are linear functions of the coordinates:

$$v_{i,\pm} = \dot{m}_{ik,\pm}(t) m_{kj,\pm}^{-1}(t) x_j, \quad (4)$$

$$E_i = \epsilon_{ij}(t) x_j. \quad (5)$$

Here summation over the repeated indices is assumed. The matrix $m_{ik,\pm}$ is a deformation matrix, $\dot{m}_{ik,\pm}$ is its time derivative and $m_{kj,\pm}^{-1}$ is the corresponding inverse matrix (see Ref. [15]).

Now we assume a spherical, cylindrical or planar symmetry of the flow, for which the deformation matrix is diagonal with equal diagonal elements, $k_{\pm}(t)$. In this case, the velocity of Lagrange element is given by $v_{\pm} = \dot{k}_{\pm} x^0$ and

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of the Euler element by $v_{\pm} = \dot{k}_{\pm}x/k_{\pm}$, and the density is $n_{\pm} = n_{0,\pm}/k_{\pm}^s$, with $n_{0,+}$ and $n_{0,-}$ being the initial values of densities of the positive and negative ions; s equals to the dimension such that $s = 1$, $s = 2$ and $s = 3$ correspond to planar, cylindrical, and spherical geometry, respectively. Substituting these functions to the equations above, we obtain a system of two nonlinear ordinary differential equations for $k_{\pm}(t)$:

$$\frac{d^2 k_+}{dt^2} = \frac{\omega_+^2}{k_+^{(s-1)}} - \frac{\omega_{\mp}^2 k_+}{k_+^s}, \quad (6)$$

$$\frac{d^2 k_-}{dt^2} = \frac{\omega_-^2}{k_-^{(s-1)}} - \frac{\omega_{\mp}^2 k_-}{k_-^s}, \quad (7)$$

where $\omega_+ = (4\pi n_{0,+} e_+^2 / M_+)^{1/2}$, $\omega_- = (4\pi n_{0,-} e_-^2 / M_-)^{1/2}$, $\omega_{\pm} = (4\pi n_{0,-} e_+ e_- / M_+)^{1/2}$, and $\omega_{\mp} = (4\pi n_{0,+} e_+ e_- / M_-)^{1/2}$. If the density of negative ions is small enough, *i.e.*, ($n_{0,-} \ll e_+ n_{0,+} / e_-$) we can neglect it with respect to a small parameter $e_- n_{0,-} / e_+ n_{0,+}$ at the first step of approximation: $n_{0,-} = 0$. This leads to the known self-similar solution of the Coulomb explosion of positive ions. Under the motion of positive ions, motion of negative ion could be calculated by test particle approximation. In the limit of $\omega_- / \Omega_- \ll 1$, we seek a solution in the form a sum of slowly varying and fast oscillating components,

$$k_-(t) = K_-(t) + \tilde{k}_-(t), \quad (8)$$

with $\langle \tilde{k}_- \rangle = 0$, where $\langle \dots \rangle$ denotes a time averaging. The component K_- corresponds to the equilibrium solution of Eq. (7) for frozen dependence on time of k_+ , *i.e.*,

$$K_-(t) = (\omega_- / \omega_{\mp})^{2/s} k_+(t). \quad (9)$$

Due to a smallness of the ratio $\omega_- / \omega_{\mp} \ll 1$ a dependence on time of the frequency $\Omega_-(t)$ is slow allowing the use of the WKB approximation. This yields the expression for the oscillating part of $k_-(t)$,

$$\tilde{k}_-(t) = [k_+(t)]^{s/4} \cos\left(\sqrt{s} \int_0^t \Omega_-(t') dt'\right), \quad (10)$$

which describes the particle oscillations with growing amplitude and decreasing frequency. From the solution, we obtain the negative ion energy is in a factor

$$\kappa = (\omega_- / \omega_{\mp})^{4/s} = (e_- n_{0,-} / e_+ n_{0,+})^{2/s} \quad (11)$$

smaller than the energy of the positive ions.

NUMERICAL SIMULATIONS

We demonstrate the implosion dynamics of negative ions by using the two-dimensional, electro-magnetic PIC code [16]. The target is a spherical cluster with the diameter of $1 \mu\text{m}$, composed of electrons, protons and negative hydrogen (H^-) ions whose densities are $1.0 n_c$, $1.1 n_c$ and $0.1 n_c$, respectively. Here $n_c = m_e \omega^2 / 4\pi e^2$ is the critical density for the laser light with the frequency of ω .

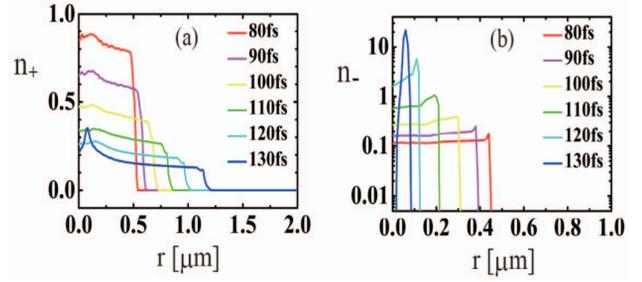


Figure 1: Radial density profiles of (a) protons and (b) negative hydrogen, H^- , ions during the Coulomb explosion and implosion. The densities are normalized on the critical density.

In this case the parameter κ given by Eq. 11 equals 0.1. The ions are assumed to be initially cold. The target is located at the center of the simulation box which has a size of $40\mu\text{m} \times 40\mu\text{m}$. The laser pulse irradiates the target from the left boundary. It propagates in the $x-$ direction and is polarized along the $y-$ direction. The pulse has a flat top shape rising up in a laser period, and peak intensity is $1.0 \times 10^{20} \text{ W/cm}^2$ with the duration of 15 fs. The laser wavelength is $1 \mu\text{m}$. The laser pulse is focused to the focal position at $x = 18\mu\text{m}$ with the diameter of $3\mu\text{m}$ (FWHM).

The time histories of radial density profile of protons and H^- ions along x -axis ($x \leq 20$) are plotted in Figs. 1(a) and 1(b), respectively, where r is defined as $r = -x + 20$. The protons expand radially due to the Coulomb explosion, having a rather flat density distribution corresponding to the self-similar solution. H^- ions move to the point $(x,y)=(19.95,20.0)$ which is $0.05 \mu\text{m}$ left to the target center. The off-centered implosion comes from the asymmetry caused by the laser irradiation. As H^- ions are accelerated inward, the electric field is induced at the center due to the accumulation of the negative charges, as is seen in Fig. 2(a). The sign of electric field at the implosion center is opposite to that of the outer region. The electric field decelerates the imploding H^- ions and attracts protons towards the center, which is seen in Fig. 1(a).

The energy spectra of protons and H^- ions are shown in Figs. 2(a) and (b), respectively. The spectra of protons exhibit flat feature corresponding to the theoretical prediction for the case of two-dimensional Coulomb explosion. The maximum energy of H^- ion is 1 MeV. We see that the negative ion energy is approximately ten times less than the

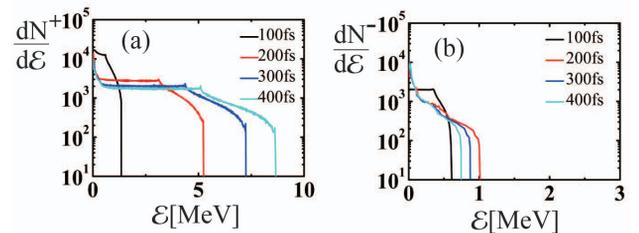


Figure 2: Time history of the energy spectra of (a) protons, and (b) H^- ions.

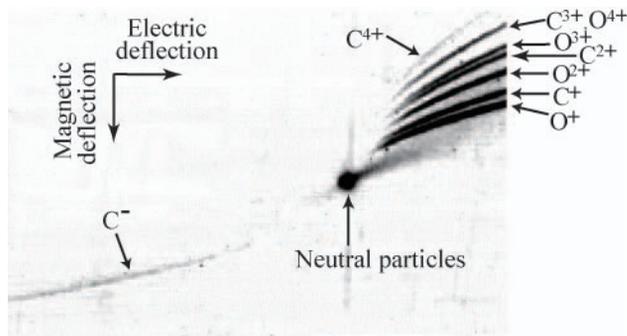


Figure 3: Ion traces recorded on CR-39 with the Thomson parabola.

energy of positive ions. This is in agreement with the theoretical model, where the parameter κ is equal to 0.1 in the simulation.

EXPERIMENTAL RESULTS

High energy negative ions are observed in the experiment with the CO₂ clusters embedded in He gas irradiated by intense laser pulse. The experiment has been conducted using JLITE-X Ti:Sapphire laser at JAEA-KPSI. The laser has the energy of 130 mJ with the pulse duration of 35 fs. The pulse is focused into the spot with 30 μm diameter in vacuum. The CO₂ clusters with the diameter equal to 0.35 μm are generated using specially designed supersonic gas jet nozzle [17]. The laser pulse contrast of 10^{-6} at the ns time scale is expected to result in the cluster heating and expansion by the pre-pulse, which results in lowering the density.

The high energy ions were detected by the Thomson parabola detector positioned in the direction of 135° from the laser axis with respect to the laser beam propagation. In Fig. 3 we show the results obtained with the Thomson parabola. We see the parabolic lines, which are produced by negative C⁻ ions as well as by the carbon ions up to C⁴⁺ ion and by the oxygen ions up to O⁴⁺ ions. The maximum energy of positive C⁴⁺ ions is 4.8 MeV, and that of the negative C⁻ ions is 0.6 MeV. This corresponds to $\kappa = 1/8$ in the model.

CONCLUSIONS

In conclusion, we use the Coulomb implosion model proposed in Ref. [14] to explain the acceleration of negatively charged ions in the laser-plasma. This mechanism is theoretically investigated and demonstrated its application to cluster or gas target plasmas by 2D PIC simulations. The Coulomb explosion leads to the positive acceleration and negative ions are accelerated by the same electric field. However, their acceleration occurs in the opposite direction with respect to the positive ion motion. In the vicinity of the electric field symmetry center, they bounce back or pass through, gaining relatively high energy. A final energy of the negative ions is several times lower than the positive ion

energy. The Coulomb implosion mechanism is applicable in the case of thin foil, self-focusing channel, and clusters.

ACKNOWLEDGMENTS

This work is supported by the grant-in-aid for young scientists (B) No. 21740404, and special Coordination Funds for Promoting Science and Technology commissioned by MEXT of Japan. The simulations are performed by using Altix3700Bx2 at JAEA Tokai.

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