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Ion Acceleration during the Coulomb Explosion of the Multispecies Clusters

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Introduction

We investigate the dynamics of sub-wavelength multispecies clusters in a relativistically strong electromagnetic (EM) wave. The cluster targets irradiated by the laser light show the properties of both underdense and overdense plasmas. In Refs. [1,2] very efficient absorption of laser energy has been demonstrated with the formation at the final stage of the clusters expansion the underdense plasma with very high temperature and X-ray emission. Such high temperature plasma makes table top fusion experiments [2] possible and provides a mechanism for ion injection into accelerators.

In the petawatt range the laser radiation can blow off all the electrons out of the cluster and make a cloud of of an electrically non-neutral plasma. The cloud undergoes the Coulomb explosion, which leads to ion acceleration. In this regime the energy spectrum and maximal energies of ions depend only on the size, density and shape of the cloud [3–5]. Hence, playing with cluster shape and composition, we can control the ion energy spectrum and their other parameters.

Here we present analytical estimations and 3D particle-in-cell (PIC) simulation of the Coulomb explosion of clusters in high-intensity electromagnetic fields.

Coulomb explosion

We consider as *the critical parameter of an intense EM wave interaction with a cluster* the ratio between the minimal energy $\mathcal{E}_{min}$, which is necessary to separate charges, and the typical kinetic energy $\mathcal{E}_{kin}$ acquired by all the electrons in the EM wave on a distance of the order of the cluster radius, $\mathcal{E}_{min}/\mathcal{E}_{kin} = (\pi/3)(R/\lambda)(\omega_{pe}/\omega)^2/a$, where $a = eE/m_e\omega c$ is the dimensionless amplitude of the EM wave, R is the cluster radius, and $\lambda = 2\pi c/\omega$ is the EM wave wavelength. If this parameter is much less than one, we have a Coulomb explosion, i.e. all the electrons abandon the cluster within a few EM wave periods and the ions form a an electrically non-neutral cloud.

Now we discuss the expansion of the spherical multispecies ion cloud under the Coulomb repulsion. The cloud comprises a heavy ion component with the electric charge $Z_\alpha e$ and mass m_α, and a small fraction light ions with their electric charge $Z_\beta e$ and mass m_β. We assume that the ions are cold, move radially, have the ratio $Z_\alpha m_\beta/Z_\beta m_\alpha \ll 1$, and their distribution inside the cluster is homogeneous. Solving equations of the β species ion motion, we obtain for the ion kinetic energy that the

ion acquires at $t \to \infty$

$$\mathcal{E}_\beta = 4\pi e^2 Z_\beta \left[2Z_\alpha n_{0\alpha} R^2 + \left(Z_\beta n_{0\beta} - Z_\alpha n_{0\alpha}\right) r_{0\beta}^2\right]/3. \quad (1)$$

Here $n_{0\alpha}$ and $n_{0\beta}$ are the ion densities in the initial configuration at $t = 0$, $r_{0\beta}$ is the initial coordinate of the β species ion ($0 < r_{0\beta} < R$), i. e. it is its Lagrange coordinate.

If the α species ion density vanishes, $n_{0\alpha} = 0$, the β -species ion energy varies from zero for $r_{0\beta} = 0$ to $\mathcal{E}_{\beta,\max} = 4\pi e^2 Z_\beta^2 n_{0\beta} R^2/3$ for $r_{0\beta} = R$. Since the ion energy is proportional to $r_{0\beta}^2$ we can calculate the ion energy spectrum $df/d\mathcal{E}_\beta$ which, due to the flux continuity in phase space, is proportional to $r_0^2 dr_0/d\mathcal{E}_\beta$. We recover the result obtained in Ref. [3]

$$\frac{df}{d\mathcal{E}_\beta} = \frac{3R}{2Z_\beta^2 e^2}\left(\frac{\mathcal{E}_\beta}{\mathcal{E}_{\beta,\max}}\right)^{1/2} \theta(\mathcal{E}_{\beta,\max} - \mathcal{E}_\beta), \quad (2)$$

where $\theta(x) = 0$ for $x < 0$ and $\theta(x) = 1$ for $x > 0$. The energy spectrum is proportional to the square root of the energy and it has a cut at $\mathcal{E}_\beta = \mathcal{E}_{\beta,\max}$ observed in the experiments discussed in Ref. [5].

In the case, when $Z_\beta n_{0\beta} \ll Z_\alpha n_{0\alpha}$, the β species ions can be considered as test particles and their motion is determined by the electric field given by the electric field of the α species ions. As follows from Eq. (1) the maximal energy of the β ions is equal to $\mathcal{E}_{\beta,\max} = 8\pi e^2 Z_\beta Z_\alpha n_{0\alpha} R^2/3$ and their minimal energy is $\mathcal{E}_{\beta,\min} = 4\pi e^2 Z_\beta Z_\alpha n_{0\alpha} R^2/3$. The energy spectrum has a form

$$\frac{df}{d\mathcal{E}_\beta} = \frac{3R\left(\mathcal{E}_{\beta,\max} - \mathcal{E}_\beta\right)^{1/2}}{2^{1/2} Z_\beta Z_\alpha e^2 \mathcal{E}_{\beta,\max}^{1/2}}\left(\frac{n_{0\beta}}{n_{0\alpha}}\right)\theta(\mathcal{E}_{\beta,\max} - \mathcal{E}_\beta)\theta(\mathcal{E}_\beta - \mathcal{E}_{\beta,\min}), \quad (3)$$

Now we assume that total electric charge of the β -species ions is of the order of but less than the total electric charge of the heavy ions, i. e. $Z_\beta n_{0\beta} \ll Z_\alpha n_{0\alpha}$. Eq. (1) gives in this case that the β species ions have a narrow energy distribution with the maximal energy equal to $\mathcal{E}_{\beta,\max} = 8\pi e^2 Z_\beta Z_\alpha n_{0\alpha} R^2/3$ and the minimal energy $\mathcal{E}_{\beta,\min} = (4\pi e^2 Z_\beta/3) R^2 (Z_\alpha n_{0\alpha} + Z_\beta n_{0\beta})$. For $Z_\beta n_{0\beta} \approx Z_\alpha n_{0\alpha}$ we have $\mathcal{E}_{\beta,\max} \approx \mathcal{E}_{\beta,\min}$, and the energy width is equal to $\Delta\mathcal{E}_\beta = (4\pi e^2 Z_\beta/3) R^2 (Z_\alpha n_{0\alpha} - Z_\beta n_{0\beta})$.

The Coulomb explosion is demonstrated in the 3D PIC simulation. The linearly polarized semi-infinite $1\mu m$ laser pulse propagates in the x-axis direction. Its peak intensity is $1.37{\cdot}10^{20} W/cm^2$, corresponding to the dimensionless amplitude $a = eE_z/m_e\omega c = 10$ (at $\lambda = 1\mu$ m). The pulse front length is 3λ. The cluster with diameter $0.2\mu m$ is placed in the cubic simulation box with edge size 10.2λ. We assume that the cluster comprises hydrogen overcritical plasma with $n_e = 100 n_{cr}$. Grid size is 1024^3, total number of quasiparticles is $3{\times}10^6$. We obtaine that all the electrons abandon the cluster in a couple of laser periods. Stripped protons undergo the Coulomb explosion and acquire energy. Their energy spectrum is agrees with the analytical result given by Eq. (2).

The increase of the maximal energy of the light ions is demonstrated in the following simulation. The cluster is made of Gold, its diameter is 0.2μ m. We assume that the ionization state of the Gold atoms is +40. The protons are distributed

homogeneously in the cluster, one proton per one atom of Gold. The corresponding plasma density is $n_e = 2119 n_{cr}$. The laser pulse is the same as in the previous simulation. In this case we obtained protons acquire significantly greater energy than in the previous simulation. The maximal energy of the Gold ions is $1.83 MeV$ per nucleon, which is much less than that of protons.

The following evident scheme shows how one can obtain a quasi monoenergetic isotropic distribution of accelerated ions A high-Z cluster is coated with a low-Z thin layer. In the Coulomb explosion of this cluster the energy spread of the low-Z ions is proportional to the thickness of the coating δR, $\Delta\mathcal{E}_\beta/\mathcal{E}_{\beta,\max} \approx \delta R/R$. The parameters of the 3D PIC simulation are the same as in the previous simulation, except the distribution of protons. In this case all the protons are initially concentrated on the cluster surface in a form of a coating, 0.02μm thick. The spectrum of protons is quasi-monoenergetic, the energy spread is of the order of 14, and protons are accelerated isotropically.

Above we assumed that the Coulomb explosion of the cluster is spherically symmetric. The effects of the cluster asymmetry were discussed in Refs. [6,7]. The golden cluster with semi-axes $a = 0.15\mu$ m and $b = 0.05\mu$ m is exposed to the laser pulse as in previous simulations. It contains approximately the same number of particles as a spherical cluster with diameter 0.2μm. Maximal instantaneous electric field due to the edge intensification is $e\mathcal{E}_{\alpha,\max}/m_e\omega c \approx 48$. This effect can cause generation of multicharged ions with strongly anisotropic spectrum.

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