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The intense laser interaction with multicluster- plasma

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The results of analytical studies and of two - and three dimensional particle in cell simulations of the ultra short high irradiance laser pulse interaction with cluster targets are presented. We present the energy spectra of the fast ions generated during the Coulomb explosion of the multi-species clusters. The ion acceleration by the radiation pressure of a super-intense laser pulse is demonstrated.

Introduction

In the present paper we investigate the dynamics of sub-wavelength clusters in a relativistically strong electromagnetic wave. As it is well known the clusters occupy an intermediate position between gaseous and solid targets: on one hand they provide very efficient absorption of the laser pulse energy in a relatively wide region, which is typical for the underdense plasmas, and on the other hand, during interaction the electromagnetic wave with the cluster targets we see such processes as the ”vacuum heating” of the electrons, the high order harmonic generation, the hard electromagnetic radiation emission, and nuclear reactions, which are typical for the laser - solid interaction [1-2].

In the experiments on the laser cluster interaction a number of phenomena was observed: very efficient absorption of laser energy has been demonstrated as well as the formation of underdense plasmas with very high temperature, X-ray, and neutron emission. Such high temperature plasma makes table top fusion experiments possible. Fast ions in laser-cluster interaction were generated under conditions when collisional absorption and heating of the cluster plasma are dominating processes. At sufficiently high intensities the laser light can blow off electrons from atoms in a sub-wavelength cluster almost instantaneously, without secondary processes of heating and collisions. Under these conditions we can use the approximation of collisionless plasmas to describe the laser cluster interaction.

Petawatt laser pulse can blow off all the electrons from a submicron cluster and make a positively charged cloud of ions. The ion cloud expands due to repelling of equal electric charges. This is the so-called the Coulomb explosion, which leads eventually to the ion acceleration. This regime has been studied extensively within the framework of the hydrodynamics with the use of the methods of Molecular Dynamics and with the Particle in Cell (PIC) codes and analytically. In the Coulomb explosion regime the energy spectrum and the ion maximal energy depend only on the size, density and shape of the cluster. Hence, playing with cluster shape and composition, we can control the ion spectrum, angular distribution.

In the present paper we present analytical estimations and the results of the 3D particle-in-cell (PIC) simulation of the high-intensity electromagnetic wave interaction with the sub-wavelength size cluster.

A cluster medium is characterized by its material (the charge state Z, and density, size (the radius, assuming circular structure), surface and internal structure (for example, multilayer coating with materials of different composition), packing function, and spatial configuration. With regard to the interaction of laser radiation with the cluster targets, the parameters such as a ratio of the cluster size to the laser light wavelength, and a ratio of the collisionless skin depth to the cluster radius are important.

Below the main attention is paid to the multispecies cluster [3-4].

Coulomb explosion of multi-species clusters

We shall use as a dimensionless parameter, that determines the regime of an intense electromagnetic wave interaction with a cluster, the ratio between the minimal energy ε_{min} , which is necessary to separate electric charges inside the cluster, and the typical kinetic energy ε_{kin} acquired by the electron in the electromagnetic wave on a distance of the order of the cluster radius,

$$\frac{\varepsilon_{min}}{\varepsilon_{kin}} = \frac{\pi}{3a_0}\left(\frac{R}{\lambda}\right)\left(\frac{\omega_{pe}}{\omega}\right). \quad (1)$$

Here $a_0 = eE_0/m_e c\omega$ is the dimensionless amplitude of the electromagnetic wave, $\lambda = 2\pi c/\omega$ is the laser pulse wavelength, ω is its frequency, and $\omega_{pe} = \sqrt{4\pi m e^2/m_e}$ is the Langmuir frequency. If the parameter given by Eq. (1) is much less than one, we have a pure Coulomb explosion, i.e. all the electrons abandon the cluster within a few electromagnetic wave periods. As a result of the Coulomb explosion of the single species cluster the ions acquire the kinetic energy which is determined by the potential energy of a sphere with the radius R, and has a positive electric charge, i.e. $\varepsilon_{kin,max} = 4\pi n e^2 R^2/3$. The ion energy spectrum is given by $N(\varepsilon_{kin}) = (3R/2e^2)\sqrt{\varepsilon_{kin}/\varepsilon_{kin,max}}\,\theta(\varepsilon_{kin,max} - \varepsilon_{kin})$.

Now we consider a two ion species cluster. It comprises a high Z heavy ion core, which is coated by a thin light ion layer. The layer thickness, δ, is assumed to be much less than the core radius,R_c. This configuration is illustrated in Fig. 1.

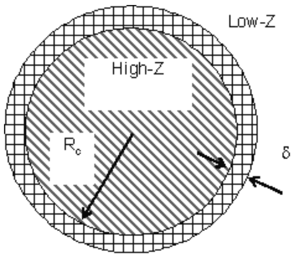

Figure 1: Initial configuration of the heavy ion cluster coated by a thin light ion layer.

As a result of the Coulomb explosion the light ion layer acquires the kinetic energy equal to the electrostatic potential at the cluster surface multiplied by the light ion electric charge. The light ion energy spectrum is as narrow as narrow the coating is, i.e. the energy width is approximately given by $\Delta\varepsilon_{kin}/\varepsilon_{kin} \approx \delta/R_c$.

In Fig. 2a we present the results of the 3D PIC simulations of the high intensity laser radiation with the coated cluster. In this case the Au cluster with the radius $R_c = 0.1\mu m$ and the electric charge per ion, Z=40, is coated by a thin hydrogen layer with the thickness equal to $\delta = 0.01\mu m$. The cluster is placed in the cubic simulation box with edge size 10.2λ. The electron density inside the cluster in the initial configuration is equal to $n = 2119 n_{nc}$. The dimensionless amplitude of the semi-infinite linearly polarized laser pulse is $a_0 = 10$, which corresponds to the intensity $1.37 \times 10^{20} W/cm^2$ (at $\lambda = 1\mu m$). The pulse front length is 3λ. The laser pulse propagates in the x-axis direction.

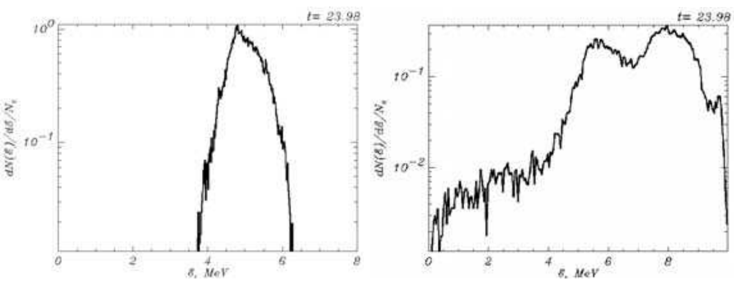

Figure 2: The the light ion energy spectrum for the coated cluster (the left hand side frame) and the light ion energy spectrum for the multispecies (Au+H) cluster(the right hand side frame)

The energy spectrum of the hydrogen layer is quasi-mono-energetic with the energy spread about 14%. The ions are accelerated isotropically.

If the light ion component is distributed inside the cluster volume homogeneously the resulting energy spectrum has a form different from the considered above. In Fig. 2b we present the results of the 3D PIC simulations of the high intensity laser radiation with the multispecies (Au+H) cluster. In this case the Au core has the radius $R_c = 0.1\mu m$ and the electric charge per ion is Z=40e. The electron density inside the cluster in the initial configuration is equal to $n = 2119 n_{cr}$. The laser pulse has the same parameters as in the previous case.

Protons acquire substantially greater energy than in the previous simulation. The maximal energy of the Gold ions is 1.83MeV per nucleon, which is much less than that of protons. The light ion energy spectrum is broad with the cut off at the maximal energy.

It is easy to show that if the minor species ion density vanishes,$n_\alpha = 0$,the β -species ion energy varies from zero to $\varepsilon_{\beta,max} = 4\pi n_\beta Z_\beta^2 e^2 R_c^2/3$. Here α stands for the hydrogen ion component and β for the Au ions. The ion energy spectrum $N,\beta(\varepsilon)$ which, due to the flux continuity in phase space, is $N_\beta(\varepsilon_{kin}) = (3R_c/2Z_\beta^2 e^2)\sqrt{\varepsilon/\varepsilon_{\beta,max}}\theta(\varepsilon_{\beta,max} - \varepsilon)$.

In the case, when the -species electric charge density is much less than the heavy ion electric charge density, $Z_\alpha n_{\alpha,0} \ll Z_\beta n_{\beta,0} Z$, the α -species ions can be considered as test particles and their motion is determined by the electric field given by the β -species ions. The energy spectrum has a form

$$N_\alpha(\varepsilon) = \frac{3R_c\sqrt{\varepsilon_{\alpha,max} - \varepsilon}}{Z_\alpha Z_\beta e^2 \sqrt{2\varepsilon_{\alpha,max}}} \left(\frac{n_{\alpha,0}}{n_{\beta,0}}\right) \theta(\varepsilon_{\alpha,max} - \varepsilon)\theta(\varepsilon - \varepsilon_{\alpha,min}) \quad (2)$$

with

$$\varepsilon_{\alpha,max} = \frac{8\pi Z_\alpha Z_\beta e^2 n_{\beta,0} R_c^2}{3}, \quad \varepsilon_{\alpha,min} = \frac{4\pi Z_\beta e^2 n_{\alpha,0} R_c^2}{3}(Z_\beta b_{\beta,0} - Z_\alpha n_{\alpha,0}) \quad (3)$$

Conclusion

We presented results of 3D PIC simulations of the ultra short high irradiance laser pulse interaction with cluster targets.

In the limit, when the radiation pressure plays a key role, the cluster is accelerated as whole, contrary to the Coulomb explosion regime, when the laser light at first blows off the electrons and then the electrically not-neutral ion core expands. In this case the energy gained by the ions is determined by the laser pulse length

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