Relativistic explosion of charged spherical microplasma

V. Yu. Bychenkov[1,3], V. F. Kovalev[2,3], A. V. Andriyash[3]

[1] *Lebedev Physical Institute, Russian Academy of Sciences, Moscow 11999, Russia*

[2] *Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow 125047, Russia*

[3] *All-Russia Research Institute of Automatics, Rosatom, Moscow 127055, Russia*

Investigations of physical effects in the interaction of short laser pulses with plasma microobjects (thin foils, clusters, nanotubes, etc.) constitute a new and rapidly developing scientific field, which could be called relativistic nano/microplasmonics. Typically, existing lasers cannot produce completely ionized large clusters with charges sufficient to accelerate ions due to the Coulomb explosion to reach relativistic energies. However, the highest currently available intensity exceeding 10^{22} W/cm^2 [1] could approach this regime. This means that experiments on the acceleration of ions to relativistic energies with the use of spherical microtargets will become possible as soon as a sufficient intensity contrast ratio is achieved for ultra-relativistic laser intensities. The ELI laser system under development should ensure an intensity of >10^{23} W/cm^2 for a 20-fs laser pulse [2]. Therefore, the physics of relativistic Coulomb explosion will be necessary. The nonlinear problem of the expansion of a uniform spherical cluster, which consists of ions with a charge sufficient to accelerate relativistic energies has been solved precisely. It has been shown that relativistic nonlinearity is responsible for the formation of an expanding shell-type structure. The space-time and energy characteristics of the ions of the relativistically exploding cluster have been found. The Coulomb explosion of the spherical microtarget consisting of heavy ions and light impurity ions is of particular interest. In this case, the light ions move faster and reaching the periphery of the cluster, are effectively accelerated by the Coulomb field of the heavy ions following them. The heavy ions acting as the Coulomb piston promote the formation of a pronounced bunch of almost monoenergetic light ions. Our analytical solution of the problem of the Coulomb explosion of a plasma microsphere with light and heavy ions indicates the possibility of generating monoenergetic light ions by the action of high-power short laser pulses on a microtarget with light and heavy atoms. Going beyond Ref. [3] we quantified how relativity (total target charge) of plasma expansion affects a monoenergeticity of the accelerated light ions.

The expansion of the spherical target with radius r_0, where ions at the initial time are at rest and uniformly distributed inside the sphere with the density n_{c0}, is considered with the help of cold collisionless hydrodynamics equations for the ion density n_1 and velocity u_1 and the

Poisson equation for self-consistent electrostatic field. The solution of these equations can be written in the parametric form [4]

$$u_1 = \frac{2qc\sqrt{\zeta(1+q^2\zeta)}}{1+2q^2\zeta}\,,\ r = \frac{h}{1-q^2}\,,\ 0 \le h \le 1\,,\ n_1 = n_{c0}(1-q^2)^3/A\,,\ \zeta_0 = \frac{\omega_{L1}^2 r_0^2}{6c^2}\,,$$

$$A{=}1{-}\frac{q^2\zeta}{(1{+}\zeta)^2(1{+}2\zeta q^2)}\left[3{+}5\zeta q^2{+}2\zeta^2 q^2 + \frac{3(1{-}q^2)\sqrt{1{+}\zeta q^2}}{2q\sqrt{1+\zeta}}\ln\frac{\sqrt{1{+}q^2\zeta}{-}q\sqrt{1{+}\zeta}}{\sqrt{1{+}q^2\zeta}{+}q\sqrt{1+\zeta}}\right],$$

$$2\sqrt{\zeta_0}t = \frac{q}{1-q^2}\sqrt{1+q^2\zeta}\frac{1+2\zeta}{1+\zeta} - \frac{1}{2}(1+\zeta)^{-3/2}\ln\frac{\sqrt{1+q^2\zeta}-q\sqrt{1+\zeta}}{\sqrt{1+q^2\zeta}+q\sqrt{1+\zeta}},\ \zeta = \zeta_0 h^2,\ (1)$$

where $\omega_{L1} = (4\pi Z_1^2 e^2 n_{c0}/M_1)^{1/2}$ is the Langmuir frequency of ions with the charge eZ_1 and the mass M_1. Here and below coordinate r, time t and energy ε_1 are normalized to r_0, c/r_0, and M_1c^2. Electrostatic field, E, of the expanding cluster can be easily found from Eq. (1). Electric field distribution is shown in Fig. 1. In the nonrelativistic limit, $\zeta \to 0$, Eq. (1) reproduces the well-known result [5, 6]. In contrast to the nonrelativistic expansion, ions are concentrated with time near the front, $r = r_f(t)$, of the expanding plasma, i.e., the formation of the shell type structure occurs (Fig. 2, left panel). The spectral distribution of accelerated ions of the cluster is given by the expression ($N_{\varepsilon_1} \equiv dN/d\varepsilon_1$):

$$N_{\varepsilon_1} = \frac{3hr_0}{2Z^2e^2q^2}\left[1+\frac{1-q^2}{2q^2}(A-1)\right]^{-1},\ (2)$$

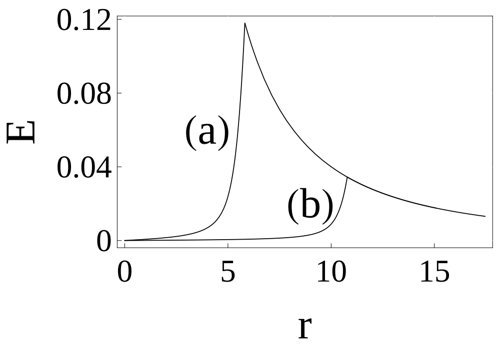

Figure 1: Electric field (in the units $2M_1c^2/Z_1er_0$) for t=5 (a) and 10 (b).

where h and q should be expressed in terms of ε_1 through the formula $\varepsilon_1 = 2q^2\zeta$ and the last equation in Eq. (1). Ion spectrum is illustrated by Fig. 2, (right panel). In the nonrelativistic limit it is $\propto \sqrt{\varepsilon_1}$. The energy spectrum of relativistic ions is rather wide as in the nonrelativistic case. The position of the front $r_f(t)$ of the expanding plasma is defined by the last equation in (1) taking into account the following change of variables: $\zeta \to \zeta_0$ and $q \to \sqrt{1-1/r_f}$.

In view of applications, it is desirable to produce monoenergetic ion beams that can be achieved with impurity light ions. In this case the heavy ions acting as the Coulomb piston promote the formation of a pronounced bunch of almost monoenergetic light ions. We consider the case where the charge of the light ion component of the cluster is much smaller than its total charge, i.e., $Zn \ll Z_1n_1$, where $Z(Z_1)$ and n(n_1) are the charge and density of light (heavy) ions, respectively. Under the above condition, the electric field of the light ions is small and does not affect their expansion. Thus, the problem reduces to studying the motion of light impurity ions in a given field of the heavy ions, given by Eq. (1) and Fig. 1.

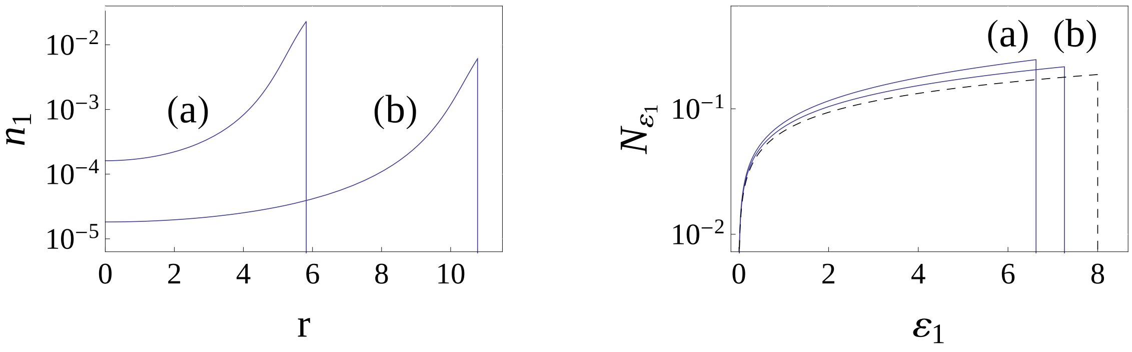

Figure 2: (left panel) Spatial distributions of ion density, n_1/n_{c0}, and (right panel) energy spectra of ions, $N_{\varepsilon_1}M_1c^2/N_1$, ($N_1$ is the total number of particles) for t=5 (a) and 10 (b). The dashed line is the spectrum in the limit $t \to \infty$.

To describe the motion of light ions in the given electric field $E(r,t)$, it is convenient to use the following equation for their radial coordinate

$$\ddot{r} = (1-\dot{r}^2)^{3/2}E(t,r)\,, \quad r_{|t=0} = \rho\,, \quad \dot{r}_{|t=0} = 0\,. \tag{3}$$

Here accelerating electric field is as follows

$$E(t,r) = \sqrt{a}\begin{cases} h^3/r^2, & r \le r_f\,; \\ 1/r^2, & r > r_f\,, \end{cases} \quad \sqrt{a} = 2\mu\zeta_0\,, \quad \mu = ZM_1/Z_1M\,, \tag{4}$$

where $h(r,t)$ dependence is given by Eq. (1). Solution of Eq. (3) allows one to reproduce density

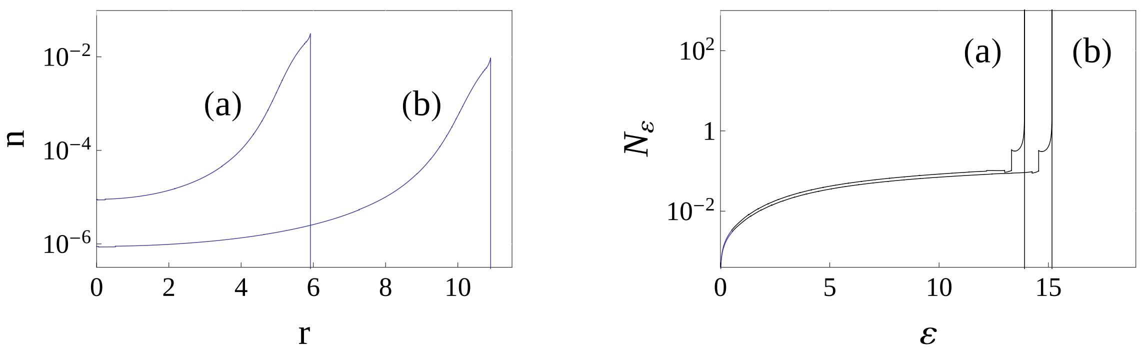

Figure 3: (left panel) Spatial distributions of light ions density, n/n_0, and (right panel) energy spectra of these ions, $N_\varepsilon Mc^2/N_0$, (N_0 is the total number of impurity particles) for t=5 (a) and 10 (b). Light ions energy is in the units of Mc^2.

space distribution and spectrum of impurity ions. They are shown in Fig. 3 for $\mu = 2$. Note that solution of Eq. (3) is given analytically both for entire space, $0 < r < \infty$, in the model of immovable bulk ions (very heavy ions, i.e. $\mu \to \infty$) and for $r \geq r_f$ in the general case (to be published somewhere). In the region $r \leq r_f$ a numerical solution is required for $\mu \neq \infty$. In accordance with Fig. 3 impurity ions form a shell structure better pronounced than for the bulk ions (cf. Fig. 2) and show monoenergetic feature. Monoenergetic light ions spectrum has already been demonstrated by the nonrelativistic solution [3]. Similar monoenergeticity exists also in a relativistic case. However, it deteriorates as far as a parameter $\omega_{L1} r_0/c$ increases. At the same time, for $\omega_{L1} r_0/c < 1$ significant part of impurity ions is still monoenergetic having a higher energy than in the nonrelativistic case.

To conclude, we emphasize that the analytical solution of the problem of the relativistic Coulomb explosion of a plasma microsphere is derived for both bulk heavy ions and light impurity. The solution found indicates the possibility of generating monoenergetic light ions by the action of relativistically strong short laser pulses on a microtarget with light and heavy atoms. The experimental observation of this effect would be an important step in the way to creating sources of monoenergetic ions of GeV energies for various applications. At present, such experiments cannot be performed, because they require a high-contrast laser pulse preventing the destruction of the target before the arrival of the main pulse. However, the development of laser nanotechnologies provides hope for a fast advance in obtaining controllable high-contrast laser pulses and high-quality microtargets with a complex atom composition. In the case of success, our study provides a good basis for future experiments on a quantum radiation produced by rapidly moving sources in the vacuum [7].

This work was supported by the Russian Foundation for Basic Research (project nos. 10-02-91060NCNIa, 11-01-00267a, and 12-02-00231a).

References

[1] V. Yanovsky, V. Chuykov, G. Kalinichenko, et al., Opt. Express **16**, 2109 (2008).

[2] http://www.extreme_light_infrastructure.eu.

[3] I. A. Andriyash, V. Yu. Bychenkov, and V. F. Kovalev, JETP Lett. **87**, 623 (2008).

[4] V. Yu. Bychenkov and V. F. Kovalev, JETP Lett. **94**, 97 (2011).

[5] A. E. Kaplan, B. Y. Dubetsky, and P. L. Shkolnikov, Phys. Rev. Lett. **91**, 143401 (2003).

[6] V. F. Kovalev and V. Yu. Bychenkov, Plasma Phys. Rep. **31**, 178 (2005).

[7] R. Pettorino and G.A. Vilkovisky, Annals of Physics **292**, 107 (2001).