CUMULATION AND ACCELERATION OF IONS BY TW FEMTOSECOND LASER PULSE

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A new method of ion cumulation and acceleration at three-dimensional compression of plasma in the "light trap" created in the focal region of the high-power femtosecond laser is theoretically studied. The "light trap" is formed by delay in time of the central part of the laser pulse being focused. The cumulation degree and maximum energy of acceleration ions depending on values of the high-power femtosecond laser pulse have been investigated by numerical methods. Physical mechanisms of ion density and energy increase in the paraxial plasma zone have been discussed. The proposed method of ion cumulation and acceleration allows one to create compact bright sources of fast neutrons, nuclei for x-ray and gamma lasers, and also provides the unique possibilities of nuclear reaction initiation and isotope production.

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Terawatt (TW) lasers [1] are already going out from the category of exotic laser systems and become the operating tool in the research practice, it is true, only in the most advanced laboratories of the world yet. Now two tends are observed:

1). Physical researches making progress (for example, in plasma physics) and expansion of the range of applied problems (for example, medicine, development of setups for scientific and engineering aims) are solved by TW femto and subfemtosecond laser systems.

2). Improvements of being in existence TW, evolution of petawatt (10^{15}) and development of exawatt (10^{18}) and even zettawatt (10^{21}) laser systems [2], which allow to solve not only traditional problems of fundamental physics, but to carry out experiments under laboratory conditions in the fields of astrophysics and cosmology.

In recent years the electron and ion acceleration in the interaction of laser pulses in gas and solid targets has the most widely evolution. Experiments have been carried out using femtosecond tabletop laser systems of the table type, the focused pulses of which reached 10^{19} W/cm^2.

Now, the record results of accelerations up to 100 MeV for electrons [3] and 60 MeV for protons [4] are obtained.

A number of experimental and theoretical works [for example 3-13] was devoted to the particle acceleration in the interaction of high-power laser pulse with a plasma. In most cases the ion acceleration is due to the mechanism of so-called "Coulomb explosion". The "Coulomb explosion" event is the ion acceleration by the electrostatic field of the division of charges production at electron expel by the ponderomotive force from the focal zone of the laser radiation.

In papers [6,7] methods of charged particle acceleration for laser operation in TEM$_{01}$ mode, when the radiation focusing occurs as a ring, were proposed. In particular, in the paper [10] on such a base the method is described for the cylindrical cumulation of ions inside the ring, which are accelerated in the radial direction to their center. From numerical simulation results using pulse duration of 240 fs at FWHM and pulse power of 100 TW the authors predict the ion acceleration up to 0.2 MeV and the volume plasma compression as a factor of 100, in the cumulation cylinder of 1μm in diameter.

In this paper the method of ion acceleration and cumulation based on the application of the laser pulse configuration produced in the TEM$_{00}$ mode has been proposed. The central part of pulse is delayed relatively to its peripheral part with formation of the difference in the optical path between them $\Delta L<ct_L$, where c is the velocity of light in vacuum, t_L is the laser pulse duration [14]. To form the mentioned above optical difference in path, the laser pulse before focusing is passed through the parallel-sided plate.

Fig.1 shows the optical scheme demonstrating the realization of this method. The laser pulse generated by the laser system 1 is shown at some moment in the position A with parameters of the spatial length of $\Delta L<ct_L$ and diameter D. After passing the parallel-sided plate 2 with the transverse dimension d the central part of pulse will be delayed with regard to the peripheral part with forming the optical difference in the path Δl between them. The shape of pulse after passing the plate 2 is shown schematically in the position B. By focusing such a pulse at some time corresponding to the pulse position C the anterior front of its peripheral part will be closed up. The closed cone volume formed inside the pulse can conventionally be named as a "light trap".

The volume of the "light trap" can be calculated depending on the geometry of the optical system from the ratio

$$V \le \frac{\pi}{12} c t_L \left(\frac{d}{L_f} \right)^2 H^2,$$

where c is the velocity of light in vacuum, t_L is the laser pulse duration, d is the diameter of the parallel-sided plate, L_f is the focal distance of the focusing lens, H is the cone height of the "light trap".

Ions being inside the "light trap" will be accelerated by the electrostatic field caused by the pondermotive effects both from the peripheral and central parts of laser pulse. As a result the high-density ion bunch is formed in the focus of three-dimensional cumulation.

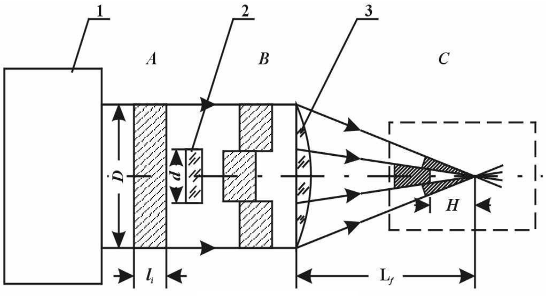


Fig.1

For realization of ion cumulation and acceleration process it is necessary that the focused ring laser pulse be propagating in the homogeneous plasma with the frequency essentially higher than the plasma frequency. We shall simulate the focused ring laser pulse intensity by the following analytical expression.

$$I(r,z,t,) = I_0 \frac{r^4}{r_L^{\,4}(z)} \exp\left[2 - \frac{2r^2}{r_L^{\,2}(z)} - \frac{(t - z/v_g)^2}{t_L^{\,2}}\right], \qquad (1)$$

where r and z are the radial and longitudinal coordinates, t is the time, v_g is the group velocity, I_0 is the maximum pulse intensity reached on the surface

$$r = r_L(z) \equiv \sqrt{r_{lin}^{\;2}\frac{z^2}{L_f^{\;2}} + r_f^{\;2}}\ ,$$

r_{lim} is the radius of the laser pulse on the focusing lens,

$$r_f = \frac{2}{\pi}\frac{\lambda L_f}{r_{lin}}$$

is the radius of the ring laser pulse on the focal plane z=0, λ is the wavelength of laser radiation. The ponderomotive force of the laser will be effect on plasma electrons

$$F_{pon} = -mc^2 \nabla \Phi_{pon},$$

where $\Phi_{pon} = \sqrt{1 + a^2/2}$ is the ponderomotive potential, $\alpha = 0{,}85 \cdot 10^{-9}\, \lambda \sqrt{I}$ is the dimensionless vector-potential of laser radiation, λ is the wavelength in microns, and I is the intensity in W/cm^2. The displacement of electrons relatively to ions will occur due to the effect of the ponderomotive force. As a result the polarized electrical field will be excited in a plasma. The equation of motion of ion has the form [11]

$$\frac{dv_i}{dt} = -\frac{m}{M} c^2 \nabla \sqrt{1 + a^2/2}\ . \qquad (2)$$

Thus, the laser pulse effects on ions by the polarized electrical field arise due to the charge separation in a plasma.

Taking into account that the laser pulse influences on ions during a very short time, it can consider that ion do not have time to displace essentially but acquire the limit initial velocity and further they move under its own momentum. Integrating the equation of motion (2) over the time interval of the focused laser pulse effect (1) on ions we shall obtained the following expression for the ion velocity components

$$v_{iz}(r_0, z_0, t_0) = -W \frac{\partial}{\partial z_0} Q(r_0, z_0),$$

$$v_{ir}(r_0, z_0, t_0) = -W \frac{\partial}{\partial r_0} Q(r_0, z_0), \qquad (3)$$

where

$$W = -\frac{m}{4M} c^2 t_L a_0^{\;2} \sqrt{\pi}\ ,$$

$$Q(r_0, z_0) = \frac{r_0^{\;4}}{r_L^{\;4}(z_0)} \exp\left[2 - \frac{r_0^{\;2}}{r_L^{\;2}(z_0)}\right],$$

r_0, z are the initial coordinates of ions, t_0 is the time of the laser pulse arrival to the point r_0, z_0, $\alpha_0 = \alpha(I_0)$. After passing of the laser pulse ions move uniformly and along the straight line.

$$z_i = v_{iz}(r_0, z_0, t_0)(t - t_0) + z_0,$$

$$r_i = v_{ir}(r_0, z_0, t_0)(t - t_0) + r_0. \qquad (4)$$

The numerical simulations of the ion cumulation process using approximation formulas (3), (4) has been performed for following parameters of the laser system:

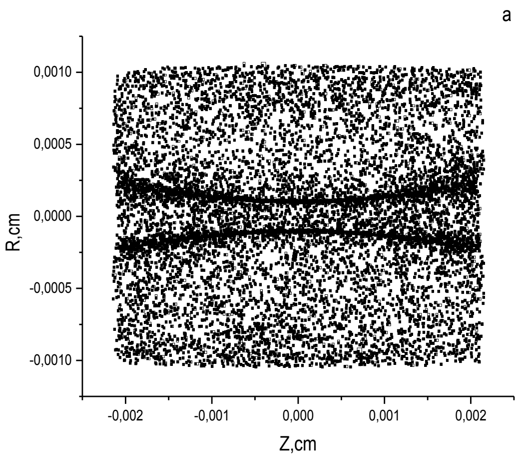
intensity, I_0…………………………10^{18} W/cm^2,
wavelength, λ……………………...1.06 μm,
pulse duration, t_L…………………..400 fs
laser pulse radius on the lens, r_{lin}….3 cm
focal distance, L_f ………………….10cm
plasma density, h …………………10^{20} cm^{-3}

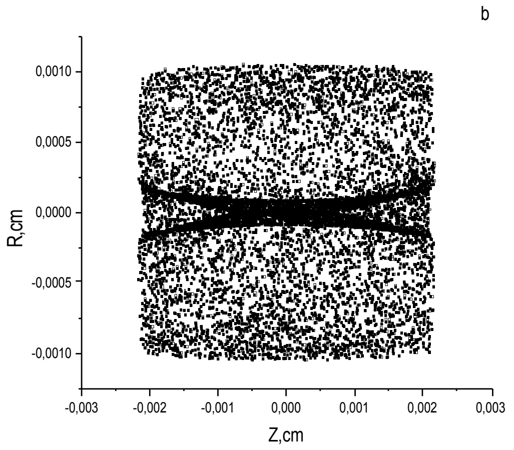
Numerical calculations have shown that the ion cumulation process is heterogeneous along the system axis and the most intensive in the zone of focus, where the radius and thickness of the ring laser pulse are minimal.

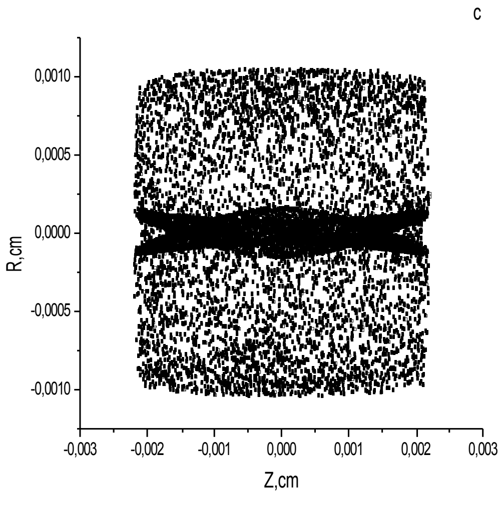
The increase of ion density more than 200 times is observed in the vicinity of a focus. With removing from the along the longitudinal direction the degree of plasma compression decreased. The average energy of ions attained ~ 300 keV.

Fig.2 shows the spatial ion configuration r, z at different moments of time. It is clearly seen, that at the beginning of the process a symmetrical shell of high density of ions is formed by the laser pulse effect. The radius of this formation is minimal in the laser pulse focus. The ion shell moves to the system axis and it is collapsed in the focal zone at the moment of 450 fs. In this case the ion density increases about 200 times and the maximum energy attains 600 keV. Further ions from force of inertia transverse the axis, and the inverse process of ions flaying away begins. The ion density in this case decreases rapidly.

Thus, in this work we have proposed the method of obtaining the focused ring laser pulse by delay of the central part of pulse by the parallel-sided plate and further pulse focusing by a lens. The simple mathematical model of the ion cumulation process of the dense plasma by such a pulse has been formulated. It has been shown that the effective ion cumulation and acceleration can be obtained in the proposed laser system.







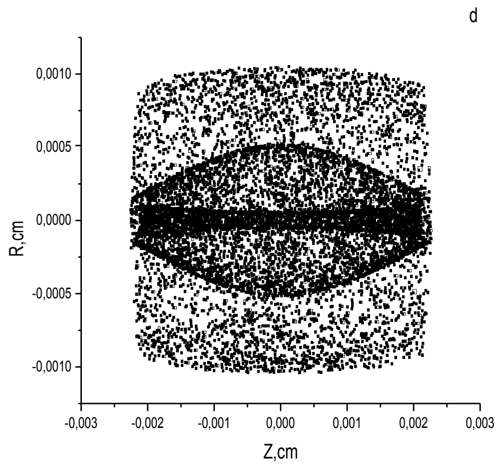


Fig.2. Ion configuration in cylindrical chamber 42μm×3μm (Z × r_0) at different moments of time (a – 0.3ps, b – 0.45ps, c – 0.6ps, d – 1ps)

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КУМУЛЯЦИЯ И УСКОРЕНИЕ ИОНОВ ТЕРАВАТТНЫМ ФЕМТОСЕКУНДНЫМ ЛАЗЕРНЫМ ИМПУЛЬСОМ

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И.Н. Онищенко, Н.И. Онищенко, А.И. Поврозин, В.И. Приступа

Теоретически исследован новый метод ускорения и кумуляции ионов при трехмерном обжатии плазмы в “световой ловушке”, создаваемой в фокальной области мощного фемтосекундного лазера. “Световая ловушка ” формируется путем задержки во времени центральной части фокусируемого импульса. Численными методами изучены степень кумуляции и максимальная энергия ускоренных ионов в зависимости от параметров мощного лазерного импульса. Обсуждены физические механизмы увеличения плотности и энергии ионов в приосевой области плазмы. Предложенный метод кумуляции и ускорения ионов позволяет создать компактные яркие источники быстрых нейтронов, среды для рентгеновского и гамма-лазеров, а также создает уникальные возможности инициирования ядерных реакций и получения изотопов.

КУМУЛЯЦІЯ ТА ПРИСКОРЕННЯ ІОНІВ ТЕРАВАТТНИМ ФЕМПТОСЕКУНДНИМ ЛАЗЕРНИМ ІМПУЛЬСОМ

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Теоретично досліджен новий метод прискорення та кумуляції при трьохвимірному стисненні плазми в “світової пастці”, що утворюється в фокальної області потужного фемптосекундного лазера. “Світлова пастка” формується шляхом затримки центральної частини лазерного імпульсу. Чисельними методами вивчені степінь кумуляції та максимальна енергія іонів в залежності от параметрів потужного лазерного імпульсу. Запропонований метод кумуляції та прискорення іонів дозволяє розробити компактні джерела швидких нейтронів середовища для рентгенівського то гамма-лазерів, а також дає унікальні можливості ініціювання ядерних реакцій і отримання ізотопів.