STABILITY OF THE HIGH-CURRENT ION BEAM COMPENSATED BY ELECTRON BEAM IN THE INDUCTION LINAC DRIFT GAP FILLED WITH THE DENSE ELECTRON CLOUD

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In the work an injection of high-current electron and ion beams in a drift gap of the linear induction accelerator with collective focusing is studied. Consideration is carried out by means of numerical simulation by PIC-method in frame of full Vlasov-Maxwell equations set. It is shown, that a filling of a drift gap with the dense electron cloud, which is confined by magnetic field of trap configuration, on the one hand, provides charge compensation. However, on the other hand, it promotes development of electron and ion beams instability. Parameters (cloud density and temperature) and conditions, at which the energy spread of pulsed high-current (the density of particles $7 \cdot 10^{17}\ \mathrm{m}^{-3}$) ion beam does not exceed several percent are chosen.

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INTRODUCTION

One of the most perspective methods of obtaining the high-current ion beams for heavy-ion nuclear fusion (HIF) is using linear induction accelerators (LIAs). The method of collective focusing of a high-current tubular ion beam proposed at the National Science Center Kharkov Institute of Physics and Technology [1, 2] allows constructing a compact accelerator that can be used as: an efficient driver for HIF and also as device for surface modification of various materials, in particular, in the radiation materials technology and other scientific research.

The mechanism of space charge and current compensation of the ion beam by an electron beam in the axisymmetric accelerating gap was investigated in [3 - 5]. The acceleration of a high-current compensated ion beam (CIB) in two cusps was studied in [5]. It is shown that the injection of thermal electrons in the drift gaps provides charge compensation of the ion beam, improving the quality of CIB acceleration.

Earlier it was shown that in the drift gap of LIA with a collective focusing, filament and high-frequency beam instabilities of compensating electron beam with a current density of 9 MA/m^2 develop. It is found, that the external longitudinal magnetic field exerts a stabilizing effect on the thermal electrons, compensating electron beam, so that the CIB quality is increased (the ion beam at the exit of LIA becomes more monoenergetic and its cross section decreases) [6].

In this paper, using three-dimensional numerical simulation, the CIB stability relatively high frequency beam and filamentation instabilities in its transport through the drift gap in the presence of external magnetic fields of various values had been studied.

The following cases of the CIB transport: 1) the simultaneous injection of the ion and electron beams in a drift gap at the initial time, 2) the injection of only the ion beam at the initial time, and compensating electron beam is injected with such time delay, that the beams come to the right end of the drift gap simultaneously, are considered.

It is shown that the compensation of the ion beam in the charge depends strongly on the external magnetic field, which prevents the transverse spreading of thermal electrons.

It is shown that in the case of simultaneous injection of the ion and electron beams virtual cathode is formed, and a part of the electron beam returns, resulting in the ion beam current becomes uncompensated and an electron beam is locked by thermal electrons, that leads to slowing down and the density increasing of the electron beam.

THE SIMULATION RESULTS

For the numerical study of instabilities it is required a powerful code which allows to solve problems of such class. In this section the CIB stability is studied using a 3-dimensional code KARAT. KARAT is fully electromagnetic code based on PiC-method (Particle-in-Cell). It designed for solving of nonstationary electrodynamics problems with complex geometry and including dynamics, in general, relativistic particles (electrons, ions, neutrals).

Usually ion LIA has magnetoisolated accelerating gap is considerably (in 10…20 times) shorter than the drift gap, so can be investigate instability of the beams only in the drift gap.

Fig. 1,a shows a cross section on the center (shown by dashed line) of the drift gap along longitudinal coordinate z, x_1 and x_2, x_3 and x_4 – internal and external dimensions of the beam, respectively. The gray color shows the presence at the initial time thermal electrons with a density $n_{the} = 5.067 \cdot 10^{17}\ \mathrm{m}^{-3}$ and a temperature of 20 keV in this area of the drift gap.

Fig. 1,b shows a cross section of the drift gap that has a cylindrical shape with a diameter of 0.2 m (transverse dimension of the computational region) and a height of 0.4 m (the longitudinal dimension of the computational region).

Three points, shown in Fig. 1,b are reference points that are chosen to illustrate various characteristics of the problem in their initial location.

Two variants of the problem have been carried out. The first case is injection of the ion beam with density $n_i = 6.967 \cdot 10^{17}$ m^{-3} and velocity $V_i = 0.27\,c$ and providing its current compensation electron beam with a density $n_e = 1.9 \cdot 10^{17}$m^{-3} and the velocity $V_e = 0.99\,c$ at the initial time. In the second case (the same parameters of the beams) at the initial time only ion beam is injected, and electron beam injection is occurred so that by the end of the drift gap ion and electron beams come simultaneously. Both these formulations of the problem are examined for the two configurations of the magnetic field shown in Fig. 2.

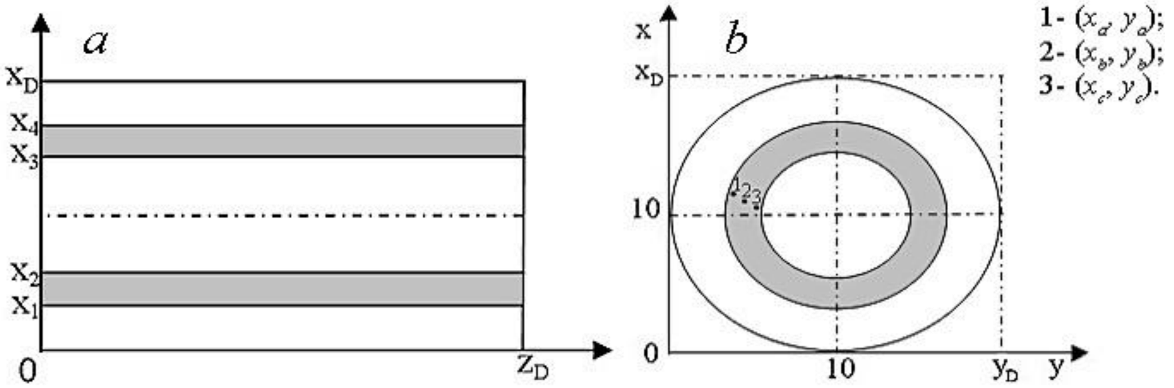

Fig. 1. Section by the plane xz of drift gap center along the z (a). Cross-section of the drift gap (b).
1 – corresponds to a point with coordinates $x_a = 4.3$ cm, $y_a = 11.9$ cm, $z_a = 5$ cm;
2 – point coordinates $x_b = 5.1$ cm, $y_b = 11.4$ cm, $z_b = 20$ cm;
3 – point coordinates $x_c = 5.9$ cm , $y_c = 10.9$ cm, $z_c = 35$ cm

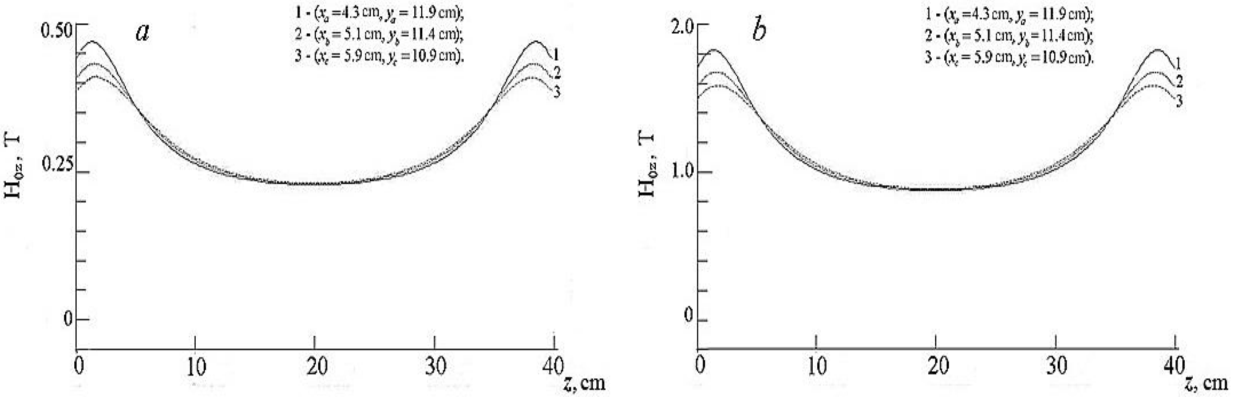

Fig. 2. The dependence of the external longitudinal magnetic field on the longitudinal coordinate z at different points x, y. (a) – the external magnetic field in the center of the drift gap corresponds $H_0 = 0.23$ T; (b) – $H_0 = 0.96$ T

The external magnetic field is set by the coils so the field on the edges of the drift gap twice larger than in the center of the system. In the first variant the external magnetic field value in the center of the drift gap is $H_0 = 0.23$ T (weak field, Fig. 2,a), in the second – $H_0 = 0.96$ T (strong field, Fig. 2,b).

Fig. 3 shows a comparison of the longitudinal distribution of the ion beam density in CIB transport through the drift gap in the presence of an external magnetic field $H_0 = 0.23$ T (after 2/5 the time of ions flight) for the three situations, the: 1) initially there is current and charge compensation of the ion beam (see Fig. 3,a) in the xz-geometry; 2) ion and electron beams are injected at the same time in the area filled with thermal electrons (see Fig. 3,b) in the xyz-geometry; 3) ion beam starts at the initial time, the electron beam is injected with a corresponding time delay in the region filled with thermal electrons (see Fig. 3,c) in the xyz-geometry.

Points 1 and 3 indicate the edge of the beam, and 2 – its center. From Fig. 3,a it is seen that in the center of the beam its density is practically equal to the initial density, and density on the edges decreased almost doubled. From Figs. 3,b,c, it is seen that in edge points dependencies of CIB density have uneven character, whereas in the center the density decreases evenly. After passing the 0.17 m, the density of the CIB has decreased by half. In the situation shown in Fig. 3,a, CIB quality is better, since at the initial moment there are no own self-consistent fields (in region along the *z* axis, on the beam width, electron beam and thermal electrons were loaded). This provided the current and the charge compensation of the ion beam, which is also in the system.

Moreover, the availability of the CIB in the system allowed even in a weak external magnetic field to keep the thermal electrons much longer than in absence of the beams in the drift gap at the initial time (see Figs. 3,b,c).

Fig. 4 illustrates the spread in the longitudinal velocity of the CIB for the same three cases, which are shown in Fig. 3. It is seen that the most monoenergetic the CIB remains in the first case, when its current and charge compensation is provided at the initial time, and the losses of thermal electrons are small (see Fig. 4,a). When ion beam and electron beam, compensating CIB in electric current, are simultaneously injected in the drift gap, and the system already has thermal electrons, the density of which should provide the charge compensation of the ion beam, the velocity spread is much larger (see Fig. 4,b). That is at the initial time an own large electric field, excited by thermal electrons, which the weak external magnetic field (see Fig. 2,a) cannot hold, is already in the system.

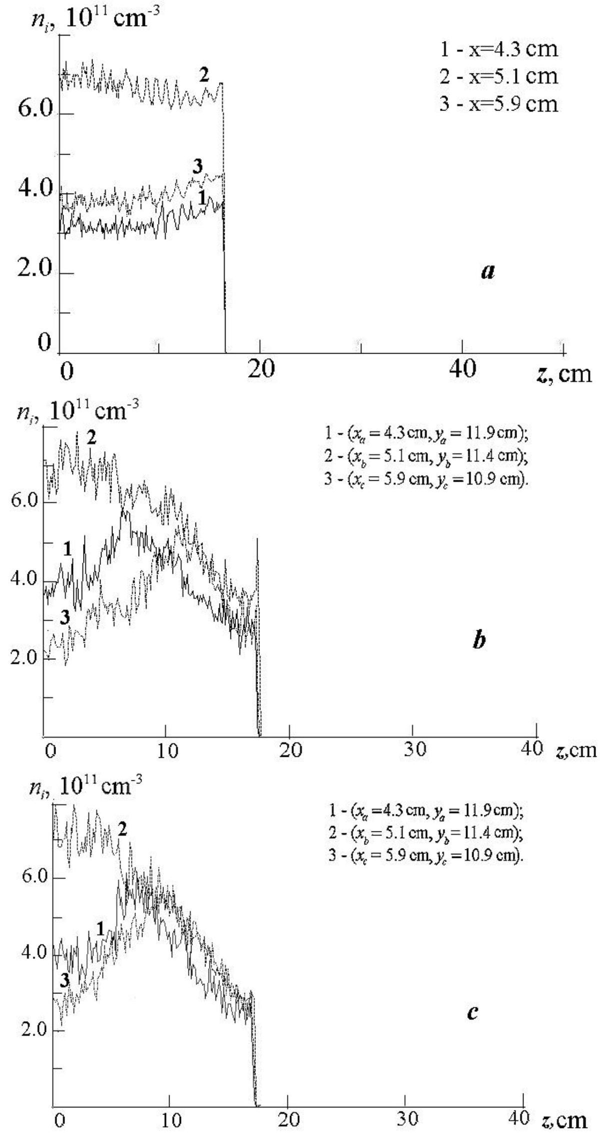

Fig. 3. The dependence of the ion beam density on the longitudinal coordinate z at different points x, y. (a) – 2d3v simulation at zero total charge and current in the beginning time; (b) – 3D simulation without time delay of the compensating electron beam; (c) – 3D simulation with time delay of the compensating electron beam; after 2ns

Moreover, electron beam, velocity of which exceeds the CIB velocity in 3.6 times, outruns the ion beam and encounters a large volume negative charge, which leads to the formation of a virtual cathode (part of the electron beam returns back and the density of the electron beam increases). As a result, the ion beam compensation is non-uniform while the own self-consistent fields, excited by the particles of the system, and the redistribution of their density degrade the CIB quality.

Some different dynamics of the particles occurs at the fixed delay of the electron beam injection in the drift gap. The ion beam current is not compensated, but CIB is almost compensated in the charge, and thermal electrons are attracted by large positive space charge of the ion beam. As a result, the CIB remains monoenergetic (see Fig. 4c). It should be noted that in general the ion beam velocity in the last two cases is practically equal to the initial velocity, and only a small amount of particles have a large acceleration.

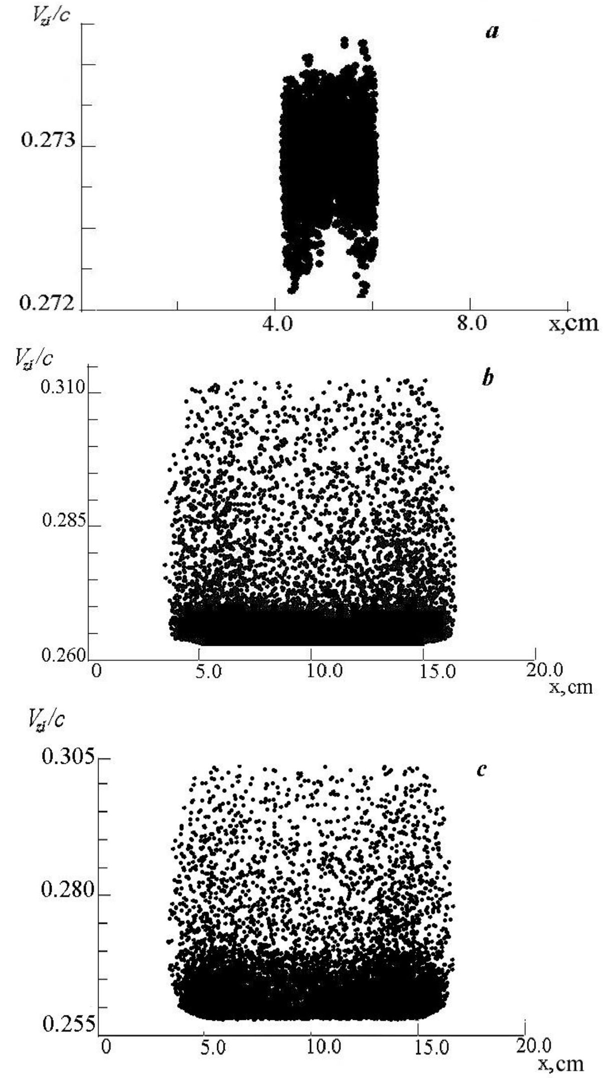

Fig. 4. The dependence of the ion beam velocity on the transversal coordinate x. (a) – 2d3v simulation at zero total charge and current in the beginning time; (b) – 3D simulation without time delay of the compensating electron beam; (c) – 3D simulation with time delay of the compensating electron beam; after 2 ns

Fig. 5 shows the CIB density depending on the transverse coordinate *x* for variants in a strong external magnetic field (see Fig. 2,b), after ≈ 0.9 time of ion beam flight through the system. It is seen that in both cases, the density of the ion beam decreased, and the only difference is that in the variant, shown in Fig. 5,a, the CIB head accelerated somewhat more, and a small part of ions has overcome a greater distance than in the second case (see Fig. 5,b). It should be noted that the CIB does not accelerate, as a whole, only the head of the ion beam, accelerated by its own space charge, has the greater speed (Fig. 6). That is, in strong magnetic field despite the fact, that the thermal electrons are confined in the system longer, than in the case of weak field, but practically after one time of CIB flight of simulation region, its quality is reduced because the thermal electrons are insufficient for the ion beam compensation.

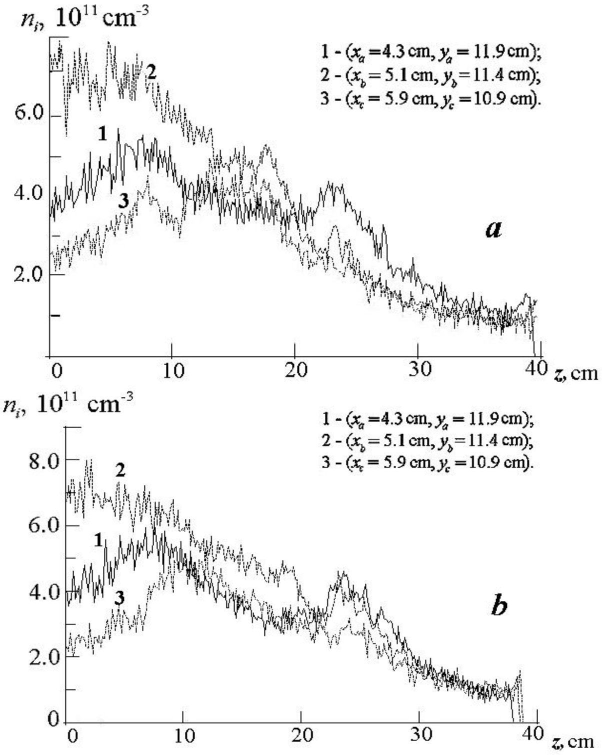

Fig. 5. The dependence of the ion beam density on the longitudinal coordinate z at different points x, y. (a) – without time delay of the compensating electron beam, (b) – with time delay of the compensating electron beam; the external magnetic field in the center of the drift gap corresponds H_0 = 0.96 T; after 4.25 ns

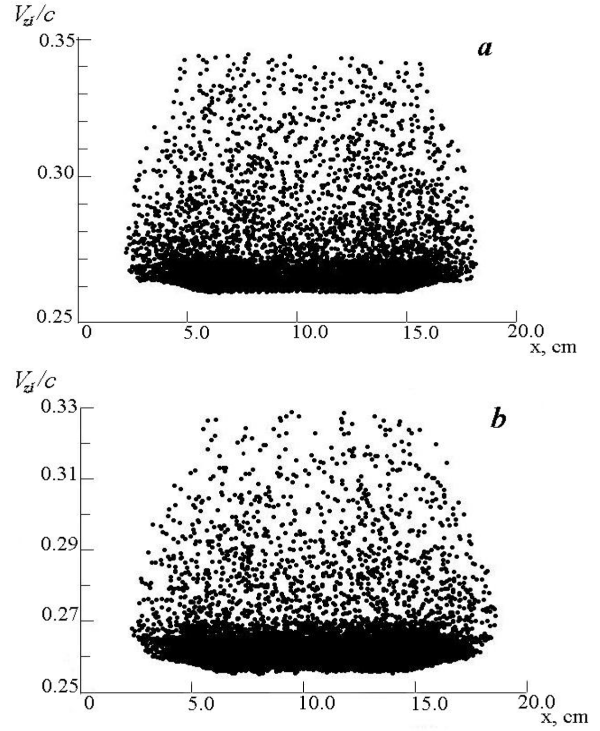

Fig. 6. The dependence of the ion beam velocity on the transversal coordinate x after 4.25ns: (a) – without time delay of the compensating electron beam; (b) – with time delay of the compensating electron beam; the external magnetic field in the center of the drift gap corresponds H_0 = 0.96 T

It is seen from Fig. 6 that, as in the case of the weak external magnetic field (Fig. 4,a,b), a small amount of ions of CIB accelerates strongly at the simultaneous injection of electron and ion beams (Fig. 6,a). In both cases, the ion beam slowed down, because there is no uniform current and charge compensation, and at the end of the drift gap density of thermal electrons is small (Fig. 6,a,b).

CONCLUSIONS

In this paper we had studied the stability of the ion beam in its transport in the drift gap of the LIA in weak and strong external magnetic fields. The variants: 1) the ion and electron beams are injected in the drift gap simultaneously, 2) compensating electron beam is injected in the drift gap with fixed delay have been considered.

It is shown that in the weak magnetic field quality of the ion beam significantly gets worse even after 2/5 time of ion beam flight through the system. Carried delay of the electron beam leads to decrease of the cross-section of the compensated ion beam (CIB). Since the weak magnetic field is not enough to keep the dense electron cloud, the ion beam in both cases becomes undercompensated.

It is found that during CIB transport through the drift gap in the strong magnetic field: the ion beam remains practically monoenergetic after the one time of ion flight; delay of the electron beam injection allows keeping the CIB charge compensation high enough. At the same time a virtual cathode does not form, and the electron beam ensures a current compensation of the ion beam. Despite the development of the filamentation and high-frequency beam instabilities, CIB quality for the indicated parameters satisfies the requirements, which are necessary for driver beam in inertial thermonuclear fusion.

So, the distribution function of the ions on longitudinal velocity is practically monoenergetic and the transverse velocity components are small enough.

Thus, the CIB quality in the strong magnetic field remains high enough at the exit from the drift gap.

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УСТОЙЧИВОСТЬ КОМПЕНСИРОВАННОГО ЭЛЕКТРОННЫМ ПУЧКОМ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В ДРЕЙФОВОМ ПРОМЕЖУТКЕ ЛИУ, ЗАПОЛНЕННОМ ПЛОТНЫМ ЭЛЕКТРОННЫМ ОБЛАКОМ

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Рассматривается инжекция сильноточных электронного и ионного пучков в дрейфовый промежуток линейного индукционного ускорителя с коллективной фокусировкой. Рассмотрение проводится с помощью численного моделирования методом макрочастиц в рамках полной системы уравнений Власова-Максвелла. Показано, что заполнение дрейфового промежутка плотным электронным облаком, удерживаемым магнитным полем ловушечной конфигурации, с одной стороны, обеспечивает зарядовую компенсацию, но, с другой стороны, способствует развитию неустойчивости электронного и ионного пучков. Выбраны параметры (плотность и температура облака) и условия, при которых разброс по энергии импульсного сильноточного ионного пучка (плотность частиц $7\cdot10^{17}$ м$^{-3}$) не превышает нескольких процентов.

СТІЙКІСТЬ КОМПЕНСОВАНОГО ЕЛЕКТРОННИМ ПУЧКОМ ПОТУЖНОСТРУМОВОГО ІОННОГО ПУЧКА У ДРЕЙФОВОМУ ПРОМІЖКУ ЛІП, ЗАПОВНЕНОМУ ЩІЛЬНОЮ ЕЛЕКТРОННОЮ ХМАРОЮ

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Розглядається інжекція потужнострумових електронного та іонного пучків у дрейфовий проміжок лінійного індукційного прискорювача з колективним фокусуванням. Розгляд проводиться за допомогою числового моделювання методом макрочастинок у рамках повної системи рівнянь Власова-Максвелла. Показано, що заповнення дрейфового проміжку щільною електронною хмарою, яка утримується магнітним полем пасткової конфігурації, з одного боку, забезпечує зарядову компенсацію, але, з іншого боку, сприяє розвитку нестійкості електронного і іонного пучків. Обрані параметри (густина і температура хмари) та умови, за яких розкид за енергією імпульсного потужнострумового іонного пучка (густина частинок $7\cdot10^{17}$ м$^{-3}$) не перевищує декількох відсотків.