THERMONUCLEAR FUSION (COLLECTIVE PROCESSES)

TRANSPORT AND ACCELERATION OF THE HIGH-CURRENT ION BEAM IN MAGNETO-ISOLATED GAP

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The possibility of transportation and acceleration of the high-current ion beam in the magneto-isolated gap has been demonstrated. Found the parameters of the system and beams (the magnetic field produced by the coils with opposing currents, the size of the system, and the parameters of the beams), under which the uniform acceleration of the high-current ion beam all along the gap length is realized. It is shown that the quality of the ion beam, during transport and acceleration, at the exit of the gap is acceptable for many technological applications.

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INTRODUCTION

It is known that the high-current ion beams (HCIB) in the linear induction accelerator (LIA) can be obtained for many important applications: for heavy-ion nuclear fusion (HIF), for surface modification of various materials, in the radiation materials science.

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 and other scientific research.

The space charge and current compensation of the ion beam by an electron beam in the axisymmetric accelerating gap was investigated in [3 - 6]. The acceleration of a high-current compensated ion beam 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 HCIB acceleration.

In [7] the dynamics of particles in the drift gap of LIA in the presence of an external magnetic field of trapping configuration has been numerically studied. The current compensation of the ion beam was performed by the electron beam.

The dynamics of the ion beam transportation in the external magnetic field in the drift gap of LIA with a collective focusing is studied. The variants of charge compensation of the HCIB in the drift gap are considered. It is shown that under chosen value and configuration of the magnetic field, using a programmed injection of additional electrons the HCIB quality can be kept high enough.

It was found that the additional electrons available at the initial time do not have a significant effect on the HCIB compensation, since the basic compensation of the ion beam is performed by the electron beam injected simultaneously with the HCIB, due to the formation of a virtual cathode. As a result, the fronts of the electron beam and HCIB almost simultaneously come to the right edge of the drift gap that contributes to its satisfactory current and charge compensation.

To ensure the HCIB charge compensation after one time of an ion flight the injection of the additional electrons from right border of the drift gap is performed. Found that the start time and duration of the injection of additional electrons, as well as their speed have the important meaning for keeping of uniform HCIB compensation.

It is shown that under the most appropriate variant of the HCIB compensation ion beam current at the exit of the drift gap is close to the original, and since the electron beam also retains its current, HCIB at the output of the system is almost compensated by the current. This is important for effective acceleration of the ion beam in the accelerating gap that is after drift gap of LIA. In additional the ion beam at the exit of drift gap is almost monoenergetic and retains its transverse dimensions. Found in [7] variant of the HCIB compensation allows to maintain the quality of HCIB required for HIF, but for reducing of the energy spread and the angular divergence of the ion beam it is necessary further improvement of the compensation method.

In this paper the transportation and acceleration of HCIB in the magneto-isolated gap of LIA have been studied. The possibility of using rough numerical simulation parameters (large spatial step and a small number of macroparticles, with retaining of the time step small enough to accumulation of errors, related to the time step, was minimal) for a preliminary study of particle dynamics. Found parameters of the beams and the system, under which transportation and acceleration of the HCIB (with saving of its current, density, cross section close to the original) are realized in the magneto-isolated gap. It should be noted that the external magnetic field of cusp configuration in the magneto-insulated gap is formed by coils with opposing currents. Under such conditions, HCIB accelerates practically uniformly (ion beam energy is increased by 2 MeV only in the region where there is the accelerating electrical field corresponding to an energy of 2 MeV), and the electron beam is decelerated and loses 2 MeV. Wherein the quality of the ion beam is sufficiently high: energy spread, cross-section are retained at the exit of the magneto-isolated gap.

1. TRANSPORT AND ACCELERATION OF THE HIGH-CURRENT ION BEAM IN MAGNETO-ISOLATED GAP

1.1. NUMERICAL MODEL

For the numerical study of the beam dynamics of the transport and acceleration a powerful 3-dimensional code KARAT [8], which allows solving problems of such class, is used. KARAT is fully electromagnetic code based on PiC-method (Particle-in-Cell). It designed for solving of non-stationary electrodynamics problems with complex geometry and including dynamics, in general, relativistic particles (electrons, ions, neutrals).

Transportation and acceleration of the HCIB in magneto-isolated gap (cusp) have been investigated.

Fig. 1 shows the geometry of the problem, where x_L – transverse and z_L – longitudinal dimensions of the system, x_{min} and x_{max} – internal and external dimensions of ion and electron (compensating current of the HCIB) beams, as well as the configuration of the external magnetic field generated by coils.

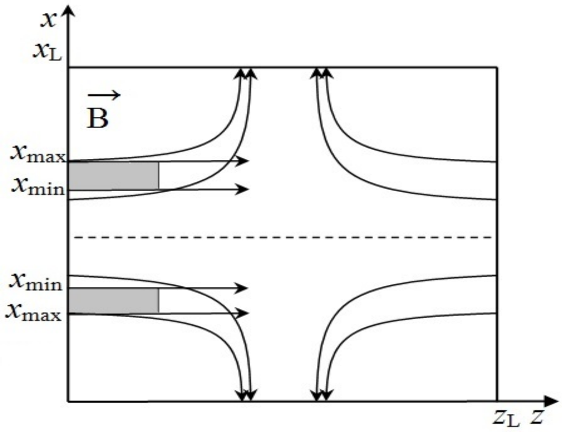

Fig. 1. The configuration of the external magnetic field, regions of beam injection

The magneto-isolated gap has a cylindrical shape with a diameter of 0.2 m (transverse dimensions x_L = 0.2 m, y_L = 0.2 m) and in the length of 0.07 m (longitudinal dimension of the computational domain). Three points in which shown the curves in Fig. 2, are the reference points, selected to illustrate the various characteristics of the problem in their original location (on the section of the beam: 0.055 and 0.06 m – points near the inner and outer radii of the beam, respectively, 0.058 m – a point on the average radius of the beam).

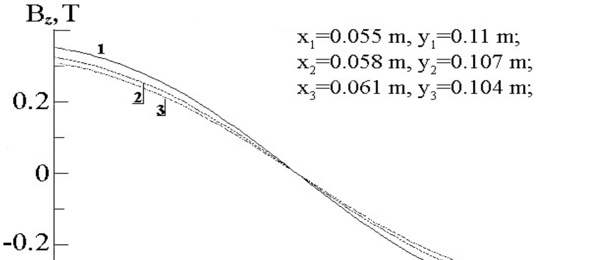

Fig. 2. Dependence of the longitudinal component of the magnetic induction of the external field on the longitudinal coordinate z in various points in x, y

Investigations were carried out using 3-dimensional simulation in xyz-geometry. Initially, there is a symmetry beams and systems along a line parallel to the *z* axis and passing through the point *x* = 0.1 m, *y* = 0.1 m, indicated in Fig. 1 by dashed line, but the dynamics of the beams leads to disruption of the initial axial symmetry along the indicated line. A Fig. 1 shows a section of the system by plane *xz*, section by *yz* plane is not illustrated, since by virtue of initial axial symmetry, is similar Fig. 1.

In the initial time the ion beam with density $n_{bi} = 7.33{\cdot}10^{17}$ m^{-3} and velocity V_{bi} = 0.27 *c* and electron beam with the same current density, with density $n_{be} = 2{\cdot}10^{17}$ m^{-3} and velocity V_{be} = 0.99 *c* are injected from the right. Internal x_{min} = 0.037 m, external – x_{max} = 0.047 m dimensions of the beams.

Two methods of numerical simulation were considered. Rough way: a small number of macroparticles (3 per cell), the maximum number of cells along the *x* I_{max} = 60, along *y* K_{max} = 60, along the *z* J_{max} = 70. Accurate way: I_{max} = 180, K_{max} = 180, J_{max} = 70, the number of macroparticles 10 particles per cell. The number of cells along the *z* axis remains unchanged, since for the longitudinal dimension of the system (0.07 m), this value is acceptable. In both cases, the Courant-Friedrich-Levy condition is performed. For brevity, the first case we shall call the "rough" and the second – "accurate". It should be noted, that accumulation of numerical errors in the dependence of number of macroparticles has been studied earlier (see, for example [9]).

Fig. 3 shows the dependence of the longitudinal component of the electrical field E_z on the longitudinal coordinate z at different times in the described above reference points, the left hand column – "rough" case, the right-hand column – "accurate". It can be seen that in all cases, the behavior of the curves retained, unlike the important details. So, after one time of an ion flight through the system τ for "rough" case the minimum of the own electric field $-9.1{\cdot}10^7$ V/m, and a maximum of $\approx 1.6{\cdot}10^7$ V/m, in the second half of the gap the field is positive (see Fig. 3,a). Whereas for the "accurate" case the minimum of the electric field $-9.9{\cdot}10^7$ V/m, and the maximum is broader and higher $\approx 1.9{\cdot}10^7$ V/m, in the second half of the magneto-isolated gap the field also becomes positive, but the curves more abruptly increase, and the electric field is more uniform (see Fig. 3,b). Such behavior of the electrical field is maintained and at other moments of times. But for the "rough" case after 10 τ, the electrical field at the outer edge of the beam after *z* = 0.04 m is positive almost till the end of the system, while in the center and on the inner edges of the beams the field is positive only on a small (0.01 m) area of the gap (see Fig. 3,c), i. e. electric field became less uniform and the acceleration of the HCIB is realized in the main for particles of outer ion beam edge. In the "accurate" case, the electric field is uniform after 10 τ (see Fig. 3,d). After 20 τ in the "rough" case, the electric field becomes some more uniform, but the area, where the field is positive, decreases (see Fig. 3,e), and in the "accurate" case, value of the electric field after maximum markedly decreased, and at the inner edge beams field is close to zero, but minimum of the field has become a little more $-1.02{\cdot}10^8$ V/m (see Fig. 3,f).

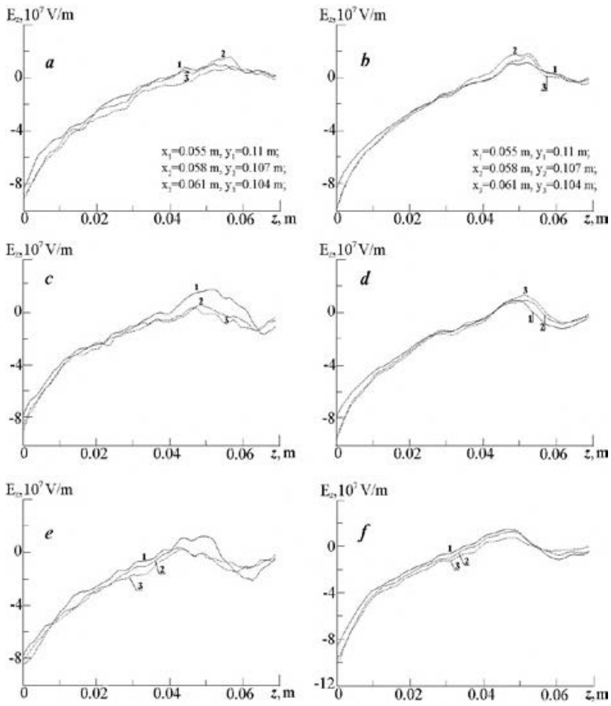

Fig. 3. Dependence of the own longitudinal electric field E_z on the longitudinal coordinate z at different points in x, y, in different moments of time; a, c, e – "rough" case; b, d, f – "accurate" case; a, b – after 1 time of ion flight of the system τ; c, d – after 10 τ; e, f – after 20 τ

Fig. 4 shows the dependence of the longitudinal component of the current of the electron beam I_{ze} on the longitudinal coordinate z in different moments of time.

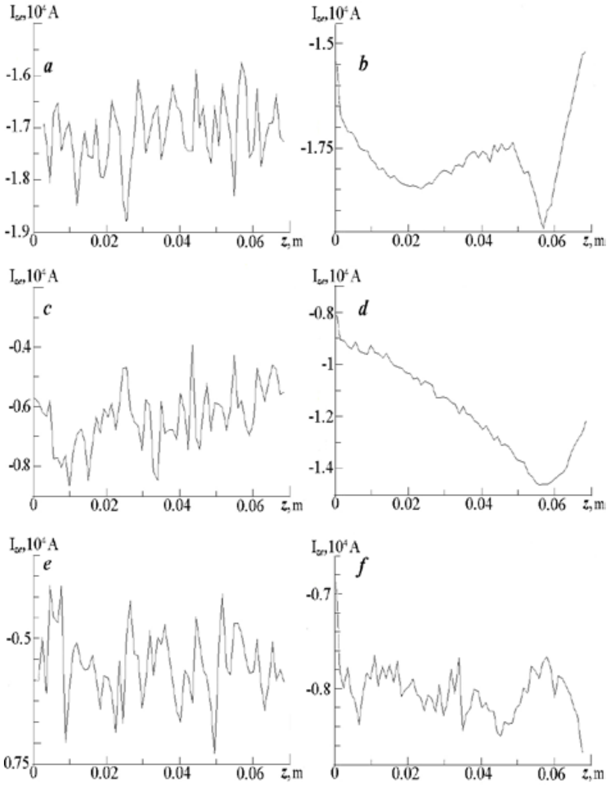

Fig. 4. The dependence of the longitudinal component of the current I_{ze} on the longitudinal coordinate z in both cases and in different moments of time; a, c, e – "rough" case; b, d, f – "accurate" case; a, b – after 1 time of ion flight τ; c, d – after 10 τ; e, f – after 20 τ

It can be seen that in the "accurate" case for the moments of time (see Figs. 4,b,d,f) appreciable current oscillations are practically absent, whereas in the "rough" case (see Figs. 4,a,c,e) the oscillation amplitude reaches 1.5 kA. Note that the not only behavior of the curves differs, but also current value, which in "accurate" case is higher than in the "rough" case more than 1 kA. For example, after 20 τ in the "rough" case a current at the exit from magneto-isolated gap is -6 kA (see Fig. 4,e), and in the "accurate" case is -8.6 kA (see Fig. 4,f). These differences are related with the using in a numerical simulation in the first case a large spatial step and a small number of particles, resulting in the accumulation of numerical errors and thus in inaccurate calculation of equations. In the "accurate" case substantial numerical noises are absent, numerical errors are minimal and do not affect the accuracy of the results. It can be seen not only from the current dependence on the longitudinal coordinate *z*, but also from the dependence of the electron beam density on the longitudinal coordinate *z* (see Fig. 5). As can be seen from Fig. 5, in the "rough" case dependences of the electron beam density are more "noisy" (have noticeable oscillations) and the maximum of density is less (see Figs. 5,a,c,e) than in the "accurate" case, where not only the electron beam density is greater at $\approx 1 \cdot 10^{17}\,\mathrm{m}^{-3}$, but the curves are smoother, uniform in the longitudinal and transverse direction (see Figs. 5,b,d,f). It should be noted that after 20 τ maximal density in the "rough" case is on the outer edge of the initial section of the beam (see Fig. 5,e), whereas in the "accurate" case is in the center (see Fig. 5,f).

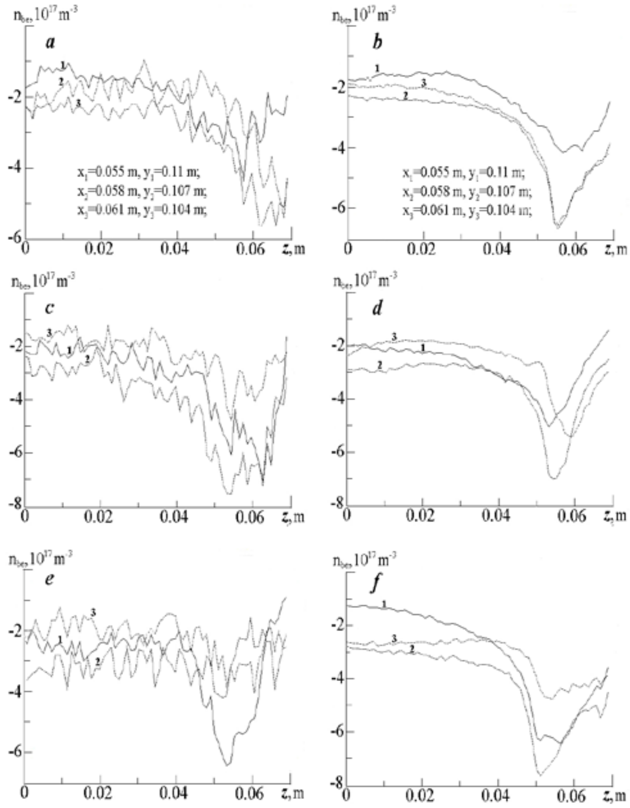

Fig. 5. The dependence of the electron beam density on the longitudinal coordinate z in various points in x, y and in different moments of time; a, c, e –"rough" case; b, d, f – "accurate" case; a, b – after 1 time of ion flight τ; c, d – after 10 τ; e, f – after 20 τ

Dynamics of HCIB acceleration is shown in Fig. 6. It can be seen that after 1 τ ion dynamics in both cases remains unchanged, except larger energy spread at the exit from the system in the “rough” case (see Fig. 6,a,c,e) than in the “accurate” (see Figs. 6,b,d,f).

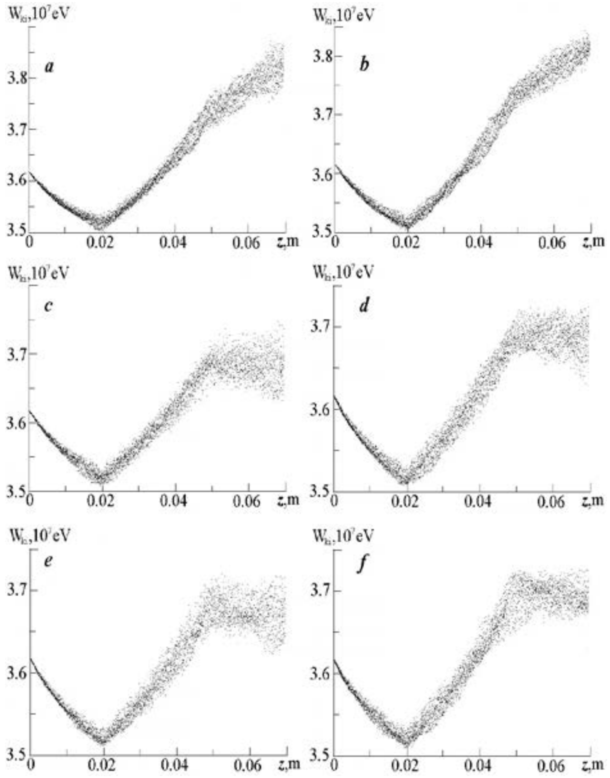

Fig. 6. The dependence of the kinetic energy of the ion beam W_{ki} on the longitudinal coordinate z in both cases and in different moments of time; a, c, e – “rough” case; b, d, f – “accurate” case; a, b – after 1 time of ion flight τ; c, d – after 10 τ; e, f – after 20 τ

Since the main purpose of the work was search for the parameters of the beams and magneto-insulated gap, providing HCIB acceleration, then, as shown in Fig. 6, preliminary calculations can be done using rough mesh and a small number of particles. This allowed significantly reducing the duration of the calculations, because numerical simulation of this system required quite a long time.

More accurate and detailed studies must not be carried out using the “rough” case, since numerical errors are significant and contribute significantly to the results of calculations, resulting in nonphysical effects. Therefore, the final simulations (after optimization of beams’ and system’s parameters) have been carried out by means of adequate numerical model, which minimized accumulation of numerical errors.

1.2. DISCUSSION OF NUMERICAL SIMULATION RESULTS

We have previously studied the acceleration of HCIB, compensated by the electron beam, in a few accelerating gaps [10]. An external magnetic field in such a system was set by special function depending on the transverse and longitudinal dimensions of the system [10]. In this paper the selection of parameters of beams and system for effectively acceleration of the HCIB has been carried out. The external magnetic field is set with the coils with opposite currents of the same value. Such a method of forming an external magnetic field can be realized in an LIA experimental model (see Fig. 2). Due to the found parameters succeeded in achieve not only HCIB transport, but and efficient acceleration of the ion beam (see Fig. 6,d) in the magneto-isolated gap.

In the case of HCIB transportation compensating electron beam after 10 τ accelerates, obtaining 2 MeV, (Fig. 7,a) and at HCIB acceleration, when an electric field has been applied between 0.02 and 0.05 m along the gap and corresponds to the energy ≈ 2 MeV (E_z = 6.6·10^7 V/m), the electron beam is slowed down, losing 2 MeV at this region of the gap (Fig. 7,b). Wherein in the beginning of magneto-isolated gap the electron beam accelerates, since in this area E_z = 0, and the space charge of the HCIB has not been compensated (initial velocity of electron beam in 3.66 times higher than the speed of the HCIB). Then, at the region, where E_z = 6.6·10^7 V/m, the electron beam slows down in the electric field, which accelerates ions. At the end of the gap, where E_z = 0, the kinetic energy of the electron beam does not change, and the velocity becomes close to the speed of the HCIB, thus electron beam density becomes higher than original one at several times, whereby the ion beam charge is practically compensated at the exit from the gap.

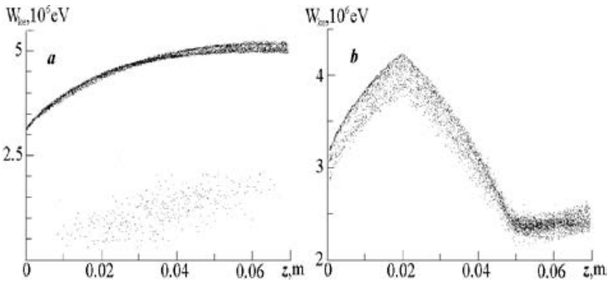

Fig. 7. The dependence of the kinetic energy of the electron beam W_{ke} on the longitudinal coordinate z after 10 τ; a – E_z = 0; b – E_z = 6.6·10^7 V/m

It should be noted, that during HCIB transport the electron beam current practically does not change (Fig. 8), whereas at the HCIB acceleration, and its value is reduced by almost in 2 times (see Fig. 4,d).

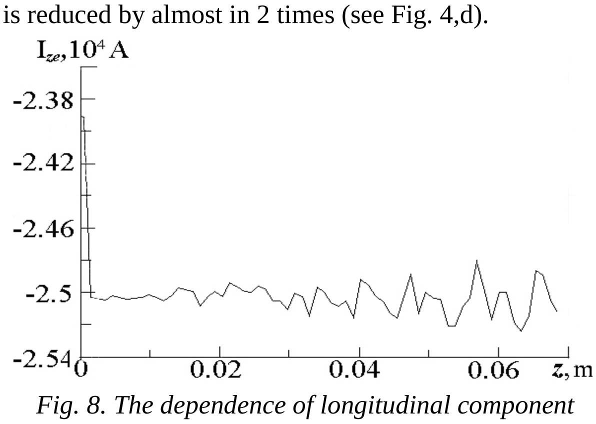

Fig. 8. The dependence of longitudinal component of the electron beam current I_{ze} on the longitudinal coordinate z after 10 τ at E_z =0

This is related to the fact that at the HCIB acceleration part of the electron beam is decelerated, and a portion is returned back, that provide the charge compensation of HCIB in the second half of the magneto-isolated gap. In the beginning of the gap, where the HCIB compensation is insufficient, the ion beam is decelerated, then accelerated in the electric field, and then in the region, where $E_z = 0$, its energy remains unchanged, since HCIB practically compensated (see Fig. 6,d). While in HCIB transport, ion beam is slowing all along magneto-isolated gap, losing to the end of the system ≈ 2 MeV (Fig. 9).

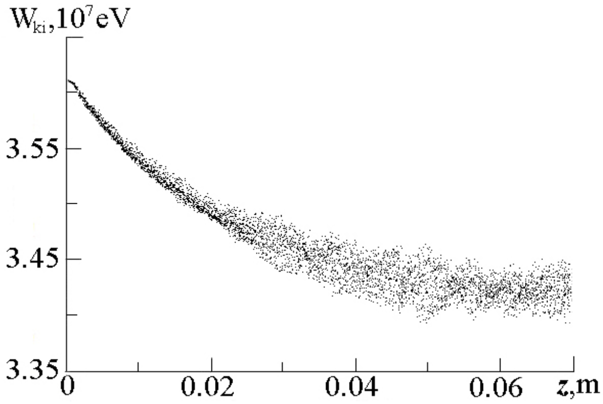

Fig. 9. The dependence of the kinetic energy of the ion beam on z after 10 τ at $E_z = 0$

It should be point out (Fig. 10) that, as in the case of transport, and in the case of acceleration HCIB current retains its value close to the initial at the exit of the system. The only difference is that during HCIB acceleration the ion beam current is more uniform along the gap.

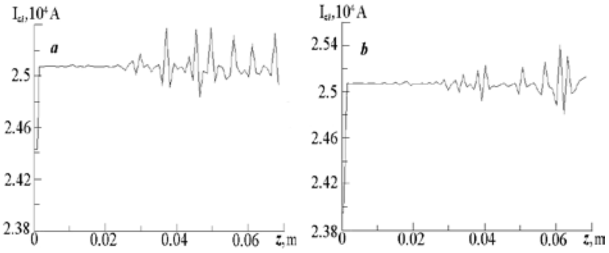

Fig. 10. The dependence of longitudinal component of the ion beam current I_z on the longitudinal coordinate z after 10 τ; a – $E_z = 0$; b – $E_z = 6.6 \cdot 10^7$ V/m

CONCLUSIONS

In this paper we have studied the dynamics of the ion beam transport and acceleration in LIA magneto-isolated gap in the presence of an external magnetic field generated by the coils with opposing currents. Considered the next variants of HCIB acceleration simulation: 1) using of simplified model (rough grid, large spatial step, a small number of macroparticles), but the time step is small enough to accumulation of errors associated with the time step was minimal; 2) using of normal model (the spatial step and the number of particulates acceptable for the given problem and its numerical solution). Using acceptable numerical model, HCIB transportation has been studied for the same parameters of the system and beams, as in two variants, noted above.

It is shown that at numerical study of particle dynamics rough numerical parameters can only be used for preliminary simulations. In this case, the next dependencies have almost the same value and character: the kinetic energy of the electron beam and the HCIB on the coordinates, velocities of the beams on the coordinates for simulations, carried out roughly and accurately. But dependencies on the density, current of the beams on coordinates differ greatly as in magnitude and character, since the numerical noise (the accumulation of numerical errors) leads to significant oscillations of the these values. Consequently, rough numerical experiment, the duration of which is low (this significantly accelerates the necessary calculations) can be carried out only for a qualitative preliminary study of particle dynamics, and for the final researches is necessary to use a numerical model that excludes a significant accumulation of numerical errors and appearing of the nonphysical effects.

Found the parameters of the beams and magneto-isolated gap, for which HCIB transport and acceleration are realized with maintaining its density, cross-section, current close to the original.

It is shown that in found conditions HCIB almost uniformly accelerated (ion beam energy is increased by 2 MeV on length where there is accelerating electric field corresponding to an energy of 2 MeV), and electron beam slowed down and lost 2 MeV.

During HCIB acceleration, ion beam is slowed down in the beginning of the gap, since because of the large difference in the speeds and densities of HCIB and electron beam, ion beam charge compensation is realized only on ≈ 30%. But as in the experimental section of LIA accelerating gap is after a drift gap, where velocities of beams are close and there is additional injection of electrons, then after docking drift and accelerating gaps in magneto-isolated gap with the HCIB will come not only slow electron beam, but also additional electrons [7]. This allows to expect that even in the beginning of the gap the ion beam does not slow down, since space charge of HCIB is compensated, that we shall present in our next works.

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ТРАНСПОРТИРОВКА И УСКОРЕНИЕ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В МАГНИТОИЗОЛИРОВАННОМ ПРОМЕЖУТКЕ

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Продемонстрирована возможность транспортировки и ускорения сильноточного ионного пучка в магнитоизолированном промежутке. Найдены параметры системы и пучков (величина магнитного поля, созданного катушками со встречными токами, размеры системы, параметры пучков), при которых осуществляется равномерное ускорение по длине промежутка. Показано, что качество ионного пучка при его транспортировке и ускорении на выходе из промежутка остается приемлемым для многих технологических применений.

ТРАНСПОРТУВАННЯ ТА ПРИСКОРЕННЯ ПОТУЖНОСТРУМОВОГО ІОННОГО ПУЧКА В МАГНІТОІЗОЛЬОВАНОМУ ПРОМІЖКУ

В.І. Карась, Є.О. Корнілов, О.В. Мануйленко, В.П. Тараканов, О.В. Федорівська

Продемонстровано можливість транспортування та прискорення потужнострумового іонного пучка в магнітоізольованому проміжку. Знайдено параметри системи та пучків (величина магнітного поля, яке створено котушками із зустрічними струмами, розміри системи, параметри пучків), при яких здійснюється рівномірне прискорення по довжині проміжку. Показано, що якість іонного пучка при його транспортуванні та прискоренні на виході з проміжку залишається прийнятною для багатьох технологічних застосувань.