DYNAMICS OF HIGH-CURRENT ION BEAM IN THE DRIFT GAP OF INDUCTION ACCELERATOR AT DIFFERENT VARIANTS OF CHARGE COMPENSATION

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In this paper the dynamics of the high-current ion beam (HIB), compensated by the electron beam by current density and partly by charge, in the drift gap (DG) of the linear induction accelerator with the collective focusing is studied. We have considered the HIB space charge compensation by thermal electrons, which are held in the DG by a magnetic field, which has mirror configuration. The dynamics of the beams at different variants of HIB space charge compensation has been studied. Found that in the presence of a programmed injection of additional electrons from the right side, the divergence of the HIB is practically absent, and its current at the exit of the DG differs slightly from the initial.

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INTRODUCTION

It is known that linear induction accelerators (LIA) can be used in different industries. Besides, high-current ion beams for heavy-ion nuclear fusion (HIF) can be obtained in LIA.

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, for example, 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 (TE) in the drift gaps allows compensating charge of the ion beam, providing the high quality of the CIB.

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

In this paper we numerically have studied the dynamics of particles in the DG with an external magnetic field of the mirror configuration. The ion beam compensation by current is performed by the electron beam. In experimental LIA electron beam can be obtained using a field emission (FE), whereby the beam is not uniform, since it goes from the surface of cathode by streams [7]. In this paper, it is assumed that in the experimental LIA, FE method will be used, so injection of the electron beam is performed by trickles.

It is shown that the proposed variants of compensation allow compensating the ion beam by charge more effectively, leading to conservation of HIB basic parameters (of quality).

It is shown that in the case of planned injection of additional electrons (AE) the ion beam current at the DG exit is almost equal to initial, and the CIB is monoenergetic.

THE SIMULATION RESULTS

For the numerical study of beams transportation dynamics a powerful 3-dimensional code KARAT [8], allowing solving problems of such class, was used. 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).

On Figs. 1,a and 1,b dashed line shows the cross section through the DG middle along the longitudinal coordinate z (x_1 and x_2, x_3 and x_4 - internal and external dimensions of the beams, respectively).

The gray color shows the presence at the initial time in this area of the DG thermal electrons with a density $n_{pe} = 5\cdot10^{17}$ m^{-3} (Fig. 1,a), $n_{pe} = 1.3\cdot10^{18}$ m^{-3} (see Fig. 1,b) and a temperature of 20 keV in all cases. Fig. 1,c shows a cross sectional view of the drift gap having a cylindrical shape with a diameter of 0.2 m (transverse dimension of the computational region) and a length of 0.4 m (longitudinal dimension of the DG). Three points, shown on Fig. 1,c, are reference points that are selected to illustrate the various characteristics of the problem in the initial area of the beams and TE location.

At the initial time the ion beam with density $n_{bi} = 6.9\cdot10^{17}$ m^{-3} and speed $V_{bi} = 0.27\,c$ and the electron beam (compensating HIB current) with the density n_{be} =

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$1.9 \cdot 10^{17}$ m^{-3} and the speed V_{be} = 0.98 *c*, where *c* - speed of light, are injected from left side. Initial current of two beams is ≈ 51.5 kA. External magnetic field is set by coils so that on edges of the drift gap, magnetic induction was twice higher than in the center of the system. Magnetic induction of the external field in the center of the drift gap B_0 = 0.96 T (Fig. 2).

Have been considered the following variants of charge compensation: 1) the DG has TE, particle density of which sufficient for the ion beam compensation (see Figs. 1,a); 2) there are TE in the beginning of the DG, after 0.5 time of ion flight τ the AE injection is realized from right side, their injection stops after 0.5 τ (see Figs. 1,b); 3) there are TE in the beginning of the DG, after τ the AE injection is realized from right side with the velocity 0.27 *c* (see Figs. 1,b); 4) there are TE in the beginning of the DG, after τ the AE injection is realized from right side with the velocity 0.5 *c* (see Fig. 1,b).

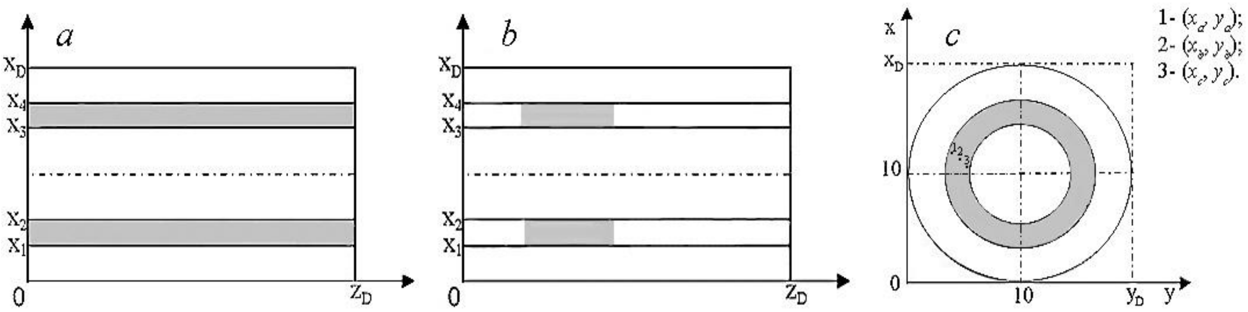

Fig. 1. Section by the plane xz of the drift gap center along z (a) and (b). Cross-section of the drift gap (c). 1 – point coordinates: x_a = 0.043 m, y_a = 0.119 m, z_a = 0.05 m; 2 – point coordinates: x_b = 0.051 m, y_b = 0.114 m; z_b = 0.2 m; 3 – point coordinates: x_c = 0.059 m, y_c = 0.109 m, z_c = 0.35 m

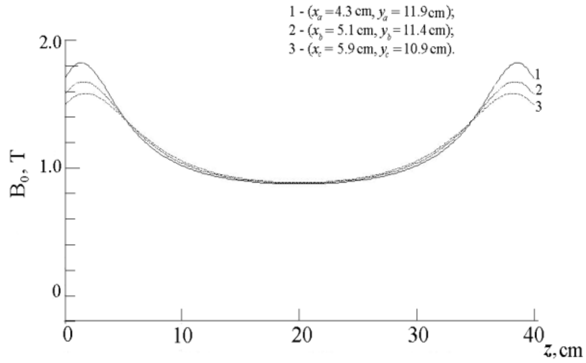

Fig. 2. The dependence of the external longitudinal magnetic field on the longitudinal coordinate z at different points x, y

Because of the substantial space charge, majority of the existing at the initial time TE leave the DG during 2 τ, weakening charge compensation of the CIB, injected in this region. That's why the ion beam transverse dimensions increase, and the current substantially decreases at the DG exit (Fig. 3,b). At that the electron beam current at the output of the DG is almost equal to the initial (Fig. 3,a).

Chosen configuration and the magnitude of the magnetic induction (see Fig. 2) allow to slow down the dispersion of thermal electrons, however, after time τ their density decreases by more than five times. For an acceptable degree of CIB compensation, the injection of additional electrons is required, what was performed in the following three (2-4 above) variants of the compensation calculations.

In the second variant of the charge compensation in the initial time TE with density of $1.3 \cdot 10^{18}$ m^{-3} are in beginning of DG, that leads to slowing down losses of particles (see Fig. 1,b), and after 0.5 τ additional electrons are injected from the right side with the current equal to the CIB current and the speed of 0.5 *c*. That is, in the second half of the DG the ion beam meets with AE, which leads to CIB partial focusing by means improving of charge compensation.

But since part of the AE are accelerated by its own space charge and flies through the right boundary, and part is reflected by space charge of the electron beam, moving toward them, the number of particles is small for the HIB compensation during the next τ. Therefore, at the time instant 2 τ CIB spreads in the transverse direction and its current substantially reduces to about 32 kA (see Fig. 3,d). At such way of charge compensation the quality of the ion beam after 2 τ slightly differs from case, when the AE injection is absent, in particular, the magnitudes of ion currents close to each other (see Figs. 3,b,d). Though, it should be noted, that at this method the ion current decreases even more than at the first. Decrease in the electron beam current at the output of the DG is small (see Figs. 3,a,c).

Third charge compensation way differs from the second by the injection speed, which is equal to 0.27 *c*, by timing switching and duration of injection. After the first τ the AE continuous injection is performed, which after two τ leads to a narrowing of the HIB transverse dimensions at the exit of DG. In turn, the current strength of the ion beam not only decreases, but also slightly higher the injection current at the output of the system (see Fig. 3,f). In this case, the HIB has parameters, close to initial and is practically compensated on the current (see Figs. 3,e,f).

The fourth method of compensation differs from the third by the AE injection velocity, which is 0.5 *c*. In the third variant the AE density at the beginning and the middle of the DG less than in the end of the system because of a large negative space charge, hindering their passage. Therefore, in the fourth variant greater value of particle velocity has been selected. This gives the AE opportunity to go through the DG with higher density and, consequently, to a greater extent compensate the HIB. After two τ ion beam towards the end of the DG has a noticeable maximum of the current, which reaches ≈ 55 kA and the related with HIB non-uniform compensation (see Fig. 3,h). At the exit of DG HIB is compensated on the current (see Figs. 3,g,h).

For all four cases the HIB charge compensation has been realized, but the first two methods have appeared ineffective. The last two variants of the charge compensation showed, that the HIB parameters do not change substantially at the exit of the system, but the compensation of the ion beam is non-uniform, which leads to current change along the DG.

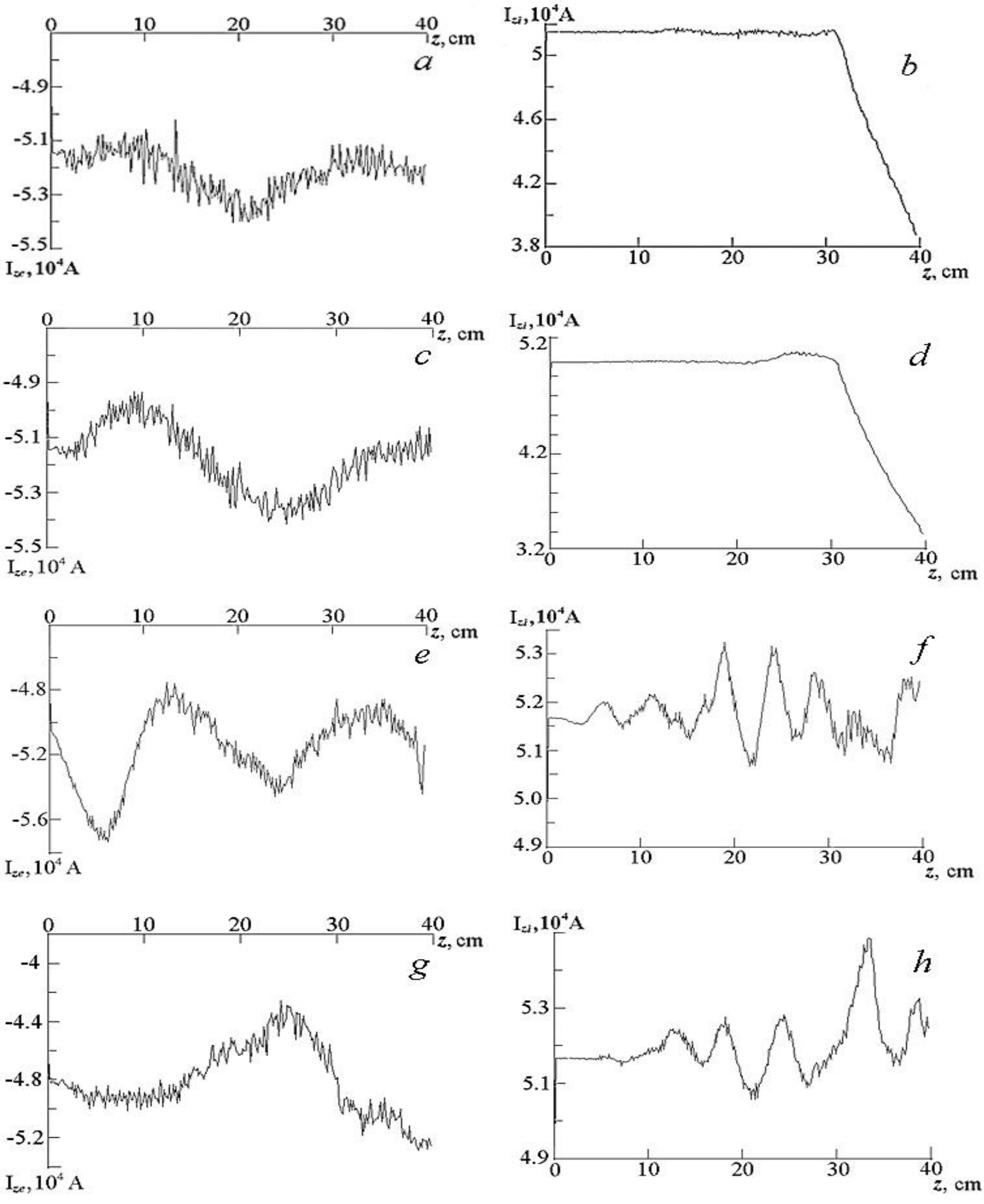

Fig. 3. The dependence of the electron beam (left column) and ion beam (right column) longitudinal current on the longitudinal coordinate z after 2 τ. (a, b) – AE injection is absent; (c, d) – after 0.5 τ from right side AE are injected during 0.5 τ; (e, f) – after τ from right side AE are injected with velocity 0.27 c; (g, h) – after τ from right side AE are injected with velocity 0.5 c

CONCLUSIONS

In this paper we have studied the dynamics of the ion beam transporting in an external magnetic field in the drift gap of LIA. Found, that the electron beam injection, non-uniform along the radius, has no significant effect on the dynamics of the beams.

The four variants of the HIB charge compensation have been considered. It is shown, that the selected magnitude and configuration of the magnetic field, using the AE planned injection, allows keeping the CIB quality high enough. Found that thermal electrons, existing at the initial time in the DG, are sufficient for HIB compensation practically during one τ, and only then the injection of AE is required. At the same time, the ion beam current is close to the initial at the exit of the DG, and, since the electron beam also retains his current, the HIB compensation by current at the exit of the DG been performed. This is important for the effective acceleration of the ion beam in the accelerating gap, where the beams come from the DG of LIA. Moreover, the ion beam stays monoenergetic and retains its transverse dimensions at the exit of the DG.

Thus, the CIB parameters at the exit of LIA DG in the presence of the magnetic field and optimal methods of charge compensation satisfy the requirements to the driver beam in HIF. Such the HIB may also be used for some other technological goals.

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ДИНАМИКА СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В ДРЕЙФОВОМ ПРОМЕЖУТКЕ ИНДУКЦИОННОГО УСКОРИТЕЛЯ ПРИ РАЗЛИЧНЫХ ВАРИАНТАХ ЗАРЯДОВОЙ КОМПЕНСАЦИИ

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Изучена динамика сильноточного ионного пучка (СИП), компенсируемого электронным пучком по плотности тока и частично по заряду, в дрейфовом промежутке (ДП) линейного индукционного ускорителя с коллективной фокусировкой. Рассмотрена компенсация пространственного заряда СИП тепловыми электронами, которые удерживаются в ДП магнитным полем пробочной конфигурации. Изучена динамика пучков при различных вариантах компенсации пространственного заряда СИП. Установлено, что при наличии программированной инжекции справа дополнительных электронов расходимость СИП практически отсутствует, а его сила тока на выходе из ДП отличается от начальной незначительно.

ДИНАМІКА СИЛЬНОСТРУМОВОГО ІОННОГО ПУЧКА В ДРЕЙФОВОМУ ПРОМІЖКУ ІНДУКЦІЙНОГО ПРИСКОРЮВАЧА ПРИ РІЗНИХ ВАРІАНТАХ ЗАРЯДОВОЇ КОМПЕНСАЦІЇ

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

Вивчена динаміка сильнострумового іонного пучка (СІП), що компенсується електронним пучком за густиною струму та частково за зарядом, у дрейфовому проміжку (ДП) лінійного індукційного прискорювача з колективним фокусуванням. Розглянута компенсація просторового заряду СІП тепловими електронами, які утримуються в ДП магнітним полем пробкової конфігурації. Вивчена динаміка пучків при різних варіантах компенсації просторового заряду СІП. Встановлено, що при наявності програмованої інжекції праворуч додаткових електронів розбіжність СІП практично відсутня, а його сила струму на виході з ДП відрізняється від початкової несуттєво.