DYNAMICS OF THE HIGH-CURRENT ION BEAM IN A SECTION OF THE LINEAR INDUCTION ACCELERATOR

V.I. Karas'[1,2], E.A. Kornilov[1], O.V. Manuilenko[1], V.P. Tarakanov[3,4], O.V. Fedorovskaya[1]
[1]National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;
[2]V.N. Karazin Kharkiv National University, Kharkov, Ukraine;
[3]Joint Institute of High Temperatures of RAS, Moscow, Russian Federation;
[4]National Research Nuclear University MEPhI, Moscow, Russian Federation
E-mail: karas@kipt.kharkov.ua

The dynamics of the high-current ion beam (HCIB) in a section of the linear induction accelerator (LIA), consisting of magneto-isolated accelerating gap and the two drift spaces, is studied. In the most suitable variant of the HCIB compensation by accompanying and colliding beams of electrons, the current of the ion beam at the exit of the first drift gap is close to the original.The optimization of the system parameters (the value of magnetic field produced by the coils with opposing currents, the size of the system, the parameters of the beams) at which a uniform on the length of the gap acceleration of the HCIB is achieved, has been carried out. Wherein the quality of the ion beam at the exit of the LIA section is kept acceptable for heavy-ion inertial fusion.

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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 heavy-ion nuclear fusion (HIF) and for other many important applications.

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 the radiation materials science 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 - 5]. 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 retained high enough.

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 [7] the dynamics of HCIB transport in the LIA drift gap, where the external magnetic field is formed by coils, have been studied. Several variants for charge compensation of the ion beam have been considered. It is shown that the proposed variants allow most effectively compensating the charge of the ion beam, that leads to the keeping of the basic parameters (quality) of the HCIB. It is shown that in case of a planned additional electron injection current of the ion beam at the exit of the drift gap substantially equal to the original, and the HCIB is monoenergetic.

In this paper we numerically studied the dynamics of particles in a section of the LIA in the presence of an external magnetic field. Current compensation of the HCIB is performed by an electron beam. The programmed injection of an additional electron beam has been carried for extra-compensation of the ion beam. It is shown that in the case of the planned injection of electrons toward the main electron and ion beams, current of the ion beam at the output of the LIA section is almost equal to the original one, and the HCIB, acquiring energy in the accelerating gap, remains practically monoenergetic.

THE SIMULATION RESULTS

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).

Fig. 1 shows by the geometry of the problem, where x_D – transverse and z_D – longitudinal dimensions of the system, x_2, x_3 and x_1, x_4 – 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.

The dash-dot line on Fig. 1 shows a section by xz plane through the center section of the LIA, consisting of two drift gaps of and one accelerating gap, along the longitudinal coordinate z (x_2 and x_3, x_1 and x_4 – internal and external dimensions of beams, respectively). The length of the first drift gap z_1 = 0.4 m, the length of the accelerating gap, shown on Fig. 1,a by the dotted line, z_4

= 0.07 m, in the center of which (between z_2 and z_3) is the accelerating electric field E_z, and the length of the second drift gap z_D = 0.1 m (which shortens the duration of the numerical calculations). Internal radius of the beams r_{min} = 0.028 m, external – r_{max} = 0.035 m.

The beams are axially-symmetric relatively to dash-dot line (x = 0.1 m, y = 0.1 m) only at the initial time (see Fig. 1,a). Fig. 1,b shows a cross section of a system, which has the shape of a cylinder with a diameter of 0.2 m (the transverse dimension of the computational region) and a length of 0.57 m (the longitudinal dimension of the section).

Three points, shown in Fig. 1,b, are the reference points (transverse coordinates x and y depend on the longitudinal coordinate z, i.e. $x(z)$, $y(z)$, and the total number of points, given in the task, – eight: x_1 = 0.069 m: y_1 = 0.109 m, z_1= 0.05 m, y_2 = 0.105 m, z_2= 0.2 m, y_3 = 0.106 m, z_3= 0.55 m, y_4 = 0.107 m, z_4 = 0.465 m; x_2 = 0.059 m: y_1 = 0.11 m, z_1 = 0.47 m; x_3 = 0.079 m: y_1 = 0.11 m, z_1 = 0.47 m), are selected to illustrate the various characteristics of the problem in the center, on external and internal edges of the initial area of the beams.

At the initial moment the injection is performed of ion beam with the density $n_{bi} = 6.9{\cdot}10^{17}$ m^{-3} and velocity V_{bi} = 0.27 c and compensating its current electron beam with the density $n_{be} = 1.9{\cdot}10^{17}$ m^{-3} and velocity: in the first variant V_{be} = 0.98 c in the second variant V_{be} = 0.99 c, where c – velocity of light, are injected. The direction of both beams is shown in Fig. 1,a (the beams are shown in gray). The location of additional electron beam injection at the beginning of the magneto-isolated gap is shown (see Fig. 1,a), the speed of the beam is directed toward the main beams and is V_{e2} = 0.96 c. Injector of additional electron beam by thickness of 0.05 m is located on the distance of 0.01 m from the trajectory of the beams at the initial time (see Fig. 1,a,b). This injector is selected so that the additional electron beam, moving on the respective magnetic lines of force, met with the front of the HCIB on the initial cross-section of the beams at the end of the drift gap (see Fig. 1,a).

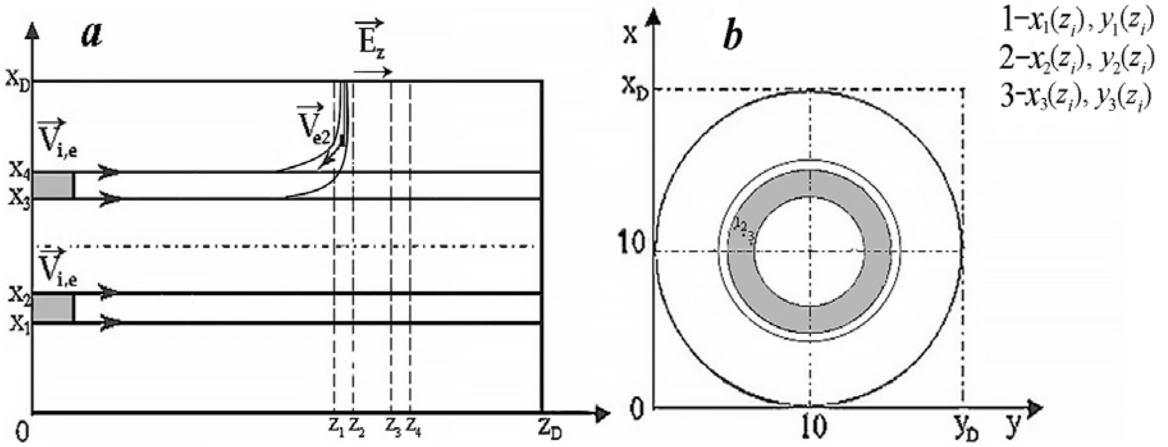


Fig. 1. Section by the plane xz of the drift gap center along z (a). Cross-section of the drift gap (b). 1 – point coordinates: $x_a(y_i, z_i)$; 2 – point coordinates: $x_b(y_b, z_b)$; 3 – point coordinates: $x_c(y_c, z_c)$

The external longitudinal electric field E_z, applied in the center of the accelerating gap (see Fig. 1,a), corresponds to the energy of 1.6 MeV and equal $E_z = 5.4{\cdot}10^7$ V/m in the first variant, (V_{be} = 0.98 c), in the second variant, (V_{be} = 0.99 c) it corresponds to the energy of 2.5 MeV, $E_z = 8.3{\cdot}10^7$ V/m. This electric field accelerates ions and decelerates electrons. The external magnetic field is formed by the coils in such way, that magnetic induction practically does not change in the drift gap, and the field itself is uniform, in the magneto-isolated accelerating gap two coils form the magnetic field of cusp configuration. Induction of the longitudinal component of the external magnetic field in the first drift gap is $B_0 \approx 0.25$ T (Fig. 2).

In this work the junction of the drift gaps with accelerating gap is performed, so problem is not only in that to carry out a qualitative compensation of the ion beam, minimize the development of instabilities in the drift gaps but provide the conditions of the HCIB acceleration in the accelerating gap. The special choice of parameters of the beams and section are related with these conditions.

Previously, it was shown that for HCIB compensation, as in the drift gap [7], as in the accelerating gap [3] it is necessary the injection of an electron beam. The current density and the cross-section of electron and ion beams should be equal. The accompanying electron beam provides a charge compensation of the ion beam in the drift gap during almost one time of ion flight through the drift gap. But since the electron beam cannot provide full charge compensation of the ion beam, after one time of ion flight of drift gap, the additional electron beam (with a density $3{\cdot}10^{17}$ m^{-3}) is injected toward the main beams.

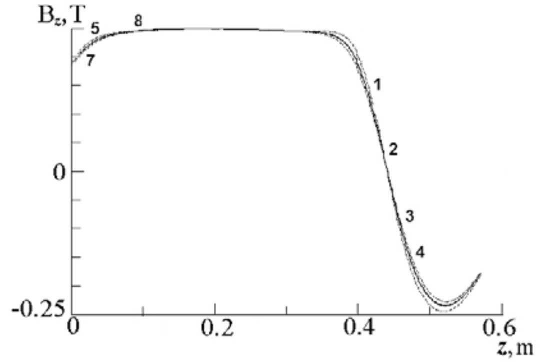
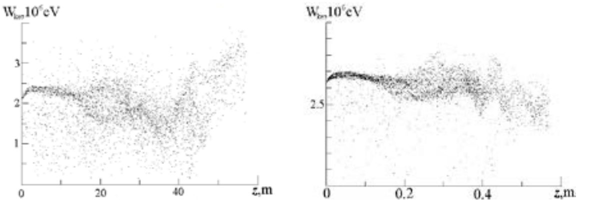


Fig. 2. The dependence of the external longitudinal magnetic field on the longitudinal coordinate z at different points x, y

Additional electron beam compensates the charge of the ion beam, but inhibits of further passing of the main electron beam to the end of the LIA section. As a result, ion beam is undercompensated in the accelerating gap, thus the transverse dimensions of the HCIB increase, and its density is two times less than initial density of the ion beam even after three times of ion flight (3τ, where τ is one time of ion flight) of section.

In that the main electron beam is accelerated in the first drift gap, then it slows down in the accelerating gap, and in the second drift gap: in the first variant (*a*) it is accelerated (Fig. 3,a), in the second variant (*b*) it slows down (Fig. 3,b). This difference in the behavior of the electron beam for different variants is related with different initial velocity of the beam. In the first variant (V_{be} = 0.98 *c*) because of the lower initial velocity of the electron beam it passes through the second half of the section and loads the HCIB, leading to slowing of the ion beam and acceleration of electron beam at the end of the section. This is connected with uncompensated positive charge of ion beam in the end of system (see Fig. 3,a). In the second variant (V_{be} = 0.99 *c*) the kinetic energy of the electron beam is larger and it does not loads HCIB so hard, as in first case. Electron beam decelerates in the accelerating gap and moves practically with a constant speed in the end of LIA section (see Fig. 3,b).



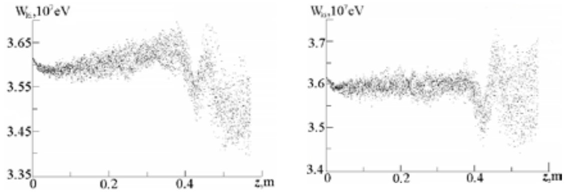
a *b*

Fig. 3. Kinetic energy of an electron beam depending on the longitudinal coordinate after 3 times of ion flight τ

In turn, the kinetic energy of the HCIB in the first variant rises along the system, increasing almost on 1 MeV, then ion beam loses about 2 MeV in the end of the first drift gap and acquires ≈ 1.5 MeV in accelerating gap, HCIB slows, again losing ≈ 2 MeV in the second drift gap (Fig. 4,a). In a second variant HCIB moves along the drift gap with energy close to the initial, then, ion beam slows down in the end of the first drift gap, losing about 1 MeV, and acquires about 2 MeV in an accelerating gap, then the HCIB kinetic energy practically does not change, although ion beam has a significant energy spread in the end of LIA section (Fig. 4,b).

From Fig. 4,b it is seen, that HCIB gets to 2 MeV in the accelerating gap while it should acquire 2.5 MeV. This occurs because of the violation of high-current conditions [3]. The density of HCIB is proportional to its self-consistent transverse magnetic B_y and transverse electric E_x and E_y fields, in which electron beam drifts in the accelerating gap. Since in accelerating gap because of HCIB undercompensation its transversal dimensions increase, consequently, ion beam density has decreased, self-fields are not high (Figs. 5 and 6) for both variants, i. e. of the density of HCIB in the accelerating gap is not enough to provide electron drift. For example, in the first variant, the maximum transverse electric field E_x in the accelerating gap is equal to ≈ $0.7 \cdot 10^7$ V/m, in the second variant $E_x \approx 2.8\ 10^7$ V/m (see Figs. 5,a,b).

It should be noted that in the accelerating gap transverse electric field E_x is less than the external electric field, although due to the large transverse separation of the ion and electron beams it is sufficiently significant, unlike the self-consistent magnetic field B_y, which in the first variant is equal to about 0.005 T, and in the second variant about 0.02 T (see Figs. 6,a,b). It is seen that the self-consistent fields, which provide drift of electrons in the accelerating gap is several times greater in the second variant than in the first, which results in more efficient acceleration and lower deceleration in the end section in the second variant (see Fig. 4,b).



a *b*

Fig. 4. Kinetic energy of the ion beam depending on the longitudinal coordinate after 3 times of ion flight τ

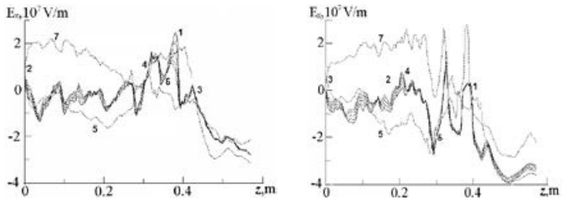


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Fig. 5. A transversal component of the electric field depending on the longitudinal coordinate after 3 times of ion flight τ

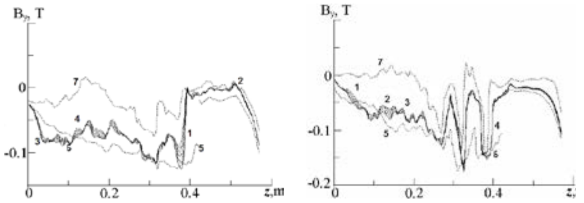

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Fig. 6. A transversal component of the magnetic field depending on the longitudinal coordinate after 3 times of ion flight τ

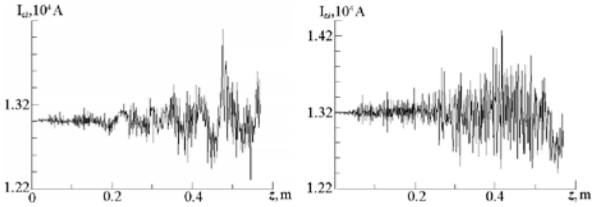

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Fig. 7. A longitudinal component of the ion beam current depending on the longitudinal coordinate after 3 times of ion flight τ

From Fig. 7 it is seen, that in both variants of the HCIB current because of non-uniform compensation has oscillations in the second half of LIA section, but it is close to initial in the end of the system. Thus, maximal ion current in the first variant is higher the initial on ≈ 1 kA and minimal ion current is lower on ≈ 1 kA, ion beam current is practically equal to the initial at the exit from the section, i.e. $I_{zi} \approx 13.2$ kA. In the second variant the maximal ion current is higher than initial on ≈ 1 kA, and a minimal current – on ≈ 0.8 kA, and HCIB current is lower than the initial 3%. i.e. $I_{zi} \approx 12.8$ kA at the exit of section (see Figs. 7,a,b).

CONCLUSIONS

In this paper we have studied the dynamics of the transport and acceleration of the compensated ion beam in an external magnetic field in the LIA section. Two variants of HCIB compensation by means accompanying electron beam are considered. It is shown that at the chosen value and configuration of the magnetic field, by means a programmed injection of the additional electron beam towards the main electron and ion beams the quality of HCIB retains high enough. It was found that the injection of an additional electron beam on one hand performs the charge HCIB compensation, on the other hand inhibits the passage of the main electron beam, required for effective acceleration of ion beam. This leads to violation of HCIB high-current conditions, respectively, to ineffective acceleration of the ion beam for case, when speed of the main electron beam V_{be} = 0.98 *c*. In this case the ion beam drags the main electron beam in the end of first drift gap and in accelerating gap, that leads to deceleration of HCIB. At a higher speed of the main electron beam (V_{be} = 0.99 *c*), the drift of the electrons is realized due to higher self-consistent fields, thus ion beam acceleration is more efficient (HCIB acquires 2 of 2.5 MeV). But in both cases at the end of the drift gap the ion beam decelerates because of its undercompensation. At the same time in the second half LIA section the electron beam, having the initial velocity V_{be} = 0.98 *c* loads the ion beam more than the electron beam, having an initial velocity V_{be} = 0.99 *c*.

It should be noted, that at the exit of the section the current of the ion beam in both cases is close to initial, and the ion energy spread does not exceed 3% in the second variant.

Thus, at the presence: the magnetic field, the injection of the accompanying electron beam with speed 0.99 *c* and programmed injection of additional electron beam; the parameters of the HCIB at the exit from LIA section are acceptable for a number of important technological applications.

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ДИНАМИКА СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В СЕКЦИИ ЛИНЕЙНОГО ИНДУКЦИОННОГО УСКОРИТЕЛЯ

В.И. Карась, Е.А. Корнилов, О.В. Мануйленко, В.П. Тараканов, О.В. Федоровская

Исследована динамика сильноточного ионного пучка (СИП) в секции линейного индукционного ускорителя (ЛИУ), состоящей из магнитоизолированного ускоряющего зазора и двух дрейфовых промежутков. В наиболее приемлемом варианте компенсации СИП сопровождающим и встречным пучками электронов, ток ионного пучка на выходе из первого дрейфового промежутка близок к первоначальному току. Проведена оптимизация параметров системы (величина магнитного поля, созданного катушками со встречными токами, размеры системы, параметры пучков), при которых достигается равномерное ускорение СИП по длине зазора. При этом качество ионного пучка на выходе из секции ЛИУ сохраняется приемлемым для инерциального термоядерного синтеза на тяжелых ионах.

ДИНАМІКА СИЛЬНОСТРУМОВОГО ІОННОГО ПУЧКА В СЕКЦІЇ ЛІНІЙНОГО ІНДУКЦІЙНОГО ПРИСКОРЮВАЧА

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

Досліджена динаміка сильнострумового іонного пучка (СІП) в секції лінійного індукційного прискорювача (ЛІП), що складається із магнітоізольованого прискорюючого зазору та двох дрейфових проміжків. В більш прийнятному варіанті компенсації СІП супроводжуючим і зустрічним пучками електронів, струм іонного пучка на виході із першого дрейфового проміжку близький до початкового. Проведена оптимізація параметрів системи (величина магнітного поля, яке створено котушками із зустрічними струмами, розміри системи, параметри пучків), при яких досягається рівномірне прискорення СІП по довжині зазору. При цьому якість іонного пучка на виході із секції ЛІП зберігається прийнятною для інерційного термоядерного синтезу на важких іонах.