NUMERICAL MODELING OF HIGH CURRENT ION BEAM TRANSPORT WITH ADDITIONAL INJECTION OF ELECTRON BEAMS IN DRIFT AND ACCELERATING GAPS OF LIA

V.I. Karas'[1, 2], E.A. Kornilov[1], O.V. Manuilenko[1], V.P. Tarakanov[3], 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

E-mail: karas@kipt.kharkov.ua

The dynamics of a high-current ion beam (HCIB) in the system, consisting of magneto-isolated accelerating gap and the drift gap (DG) of the experimental model of linear induction accelerator (LIA) has been studied. The optimization of the magnetic field geometry, the place and time of the additional electron beam injection, as well as its cross dimension is occurred. It is shown that at found parameters of the beams, the external magnetic field, the injection of the main and additional electron beams, HCIB can be compensated (HCIB and an additional electron beam currents practically equal to the initial values and are equal to each other), so that at the exit from the system, ion beam parameters are suitable for a number important technological applications.

PACS: 41.75.-i, 52.40.Mj, 52.58.Hm, 52.59.-f, 52.65.Rr

INTRODUCTION

It is known that high-current ion beams (HCIB) play an important role in various technological applications, as well as for heavy-ion nuclear fusion (HIF). Such beams can be obtained in the linear induction accelerator (LIA). The method of collective focusing of a high-current tubular ion beam, proposed in the National Scientific Center "Kharkov Institute of Physics and Technology" of National Academy of Sciences of Ukraine [1, 2], allows constructing a compact high-current ion LIA with high efficiency. Such an accelerator may be used as: effective HIF driver, for surface modification of various materials, in the radiation materials science and for 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 HCIB, improving the high quality of the ion beam.

Previously, it was shown that in the LIA drift gap with collective focusing development of the compensating electron beam filamentation instability occurs at the current density exceeding 9 MA/m^2. It is found that the external longitudinal magnetic field has a stabilizing effect on the thermal electrons, compensating HCIB, so that the ion beam at the output of the LIA becomes more monoenergetic and its cross section decreases [6].

The dynamics of HCIB transport in the LIA drift gap, where the external magnetic field is formed by coils, has been studied in [7]. The several variants of the ion beam charge compensation have been considered. It is shown that the proposed variants of compensation enable compensating the ion beam by the charge most effectively, that leads to the keeping of the CIB main parameters. It is shown that in the case of the optimized additional electrons injection, the ion beam current at the exit of the drift gap substantially equal to the original, and the CIB is monoenergetic.

The dynamics of particles in a section of the LIA in the presence of an external magnetic field has been studied. Current compensation of the ion beam has been performed by an electron beam [8]. It is shown that at the optimized electron injection towards the main electron and ion beams current at the exit of the LIA section almost equal to the original. Wherein, CIB, acquiring energy in the accelerating gap remains practically monoenergetic.

In this paper we have investigated the dynamics of the HCIB and compensating main and additional electron beams in the system, consisting of the magneto-isolated gap and drift interval of LIA experimental model. Two variants of HCIB compensation by addition electron beam have been studied. It is shown that at the chosen parameters of the external magnetic field and at the injection of the additional electron beam, HCIB is practically compensated in current and partly in charge in the second half of the accelerating gap and in the DG. This enabled keeping the HCIB quality at the exit from LIA acceptable to important scientific and technical applications.

THE RESULTS OF SIMULATION

For the numerical investigation of the beams transport dynamics a powerful 3-dimensional code KARAT [8] 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 a cross section through the center and along the (longitudinal coordinate *z*) studied system, consisting of magneto-isolated gap and DG of LIA. Magneto-isolated gap has the length z_m = 0.4 m, the length of DG is 0.4 m, the length of the system z_s = 0.8 m. Radius of the magneto-isolated gap R_m = 0.5 m. The symmetry axis of the system is shown in Fig. 1 by the dashed line passing through the point $x = 0.5$ m, $y = 0.5$ m.

At the beginning of magneto-isolated gap (left, Fig. 1) at the initial time the ion beam with a density $n_{bi} = 6.9 \cdot 10^{17}$ m^{-3} and the velocity $V_{bi} = 0.27\ c$, where c – speed of light, and the main electron beam with density $n_{be} = 1.9 \cdot 10^{17}$ m^{-3} and velocity $V_{be} = 0.99\ c$, compensating of the HCIB current, are injected. At start time currents of the beams are equal $I_{zbe} = I_{zbi} = 13.2$ кА. The direction of the two beams is shown in Fig. 1 on the left. Inner size of the beams – $r_{min} = 0.028$ m, outer – $r_{max} = 0.035$ m. The beams are axially symmetric with respect to the dashed line only at the initial time (Fig. 1.). Fig. 1 also shows the injection of the addition electron beam with velocity $V_{eb}^{add} = 0.99\ c$ and current $I_{zbe}^{add} = 13.2$ кА in the magneto-insulated gap. Injector of the additional electron beam has a thickness of 0.003 m. The place of injection is selected so that the additional electron beam moving on the appropriate magnetic lines of force, accompanied the HCIB in the second half of the magneto-isolated gap and in the DG at the initial cross-section of the main electron beam and CIB.

It should be noted, that the dynamics of particles is studied in the system, which has dimensions and the magnetic field value, corresponding to the experimental model LIA with a collective focusing.

An external magnetic field in the gap created by the coils in the magneto-isolated gap with counter currents and has a cusp configuration. Coils, placed in magneto-isolated gap, have turns, both in the transverse (35 turns) and longitudinal (15 turns) directions. The transverse dimension of the coils is 0.5 m and a longitudinal is 0.18 m. In the DG the magnetic field is formed by the coils of the same size and radius, therefore the magnetic induction along the drift gap remains practically unchanged, and the field itself is uniform.

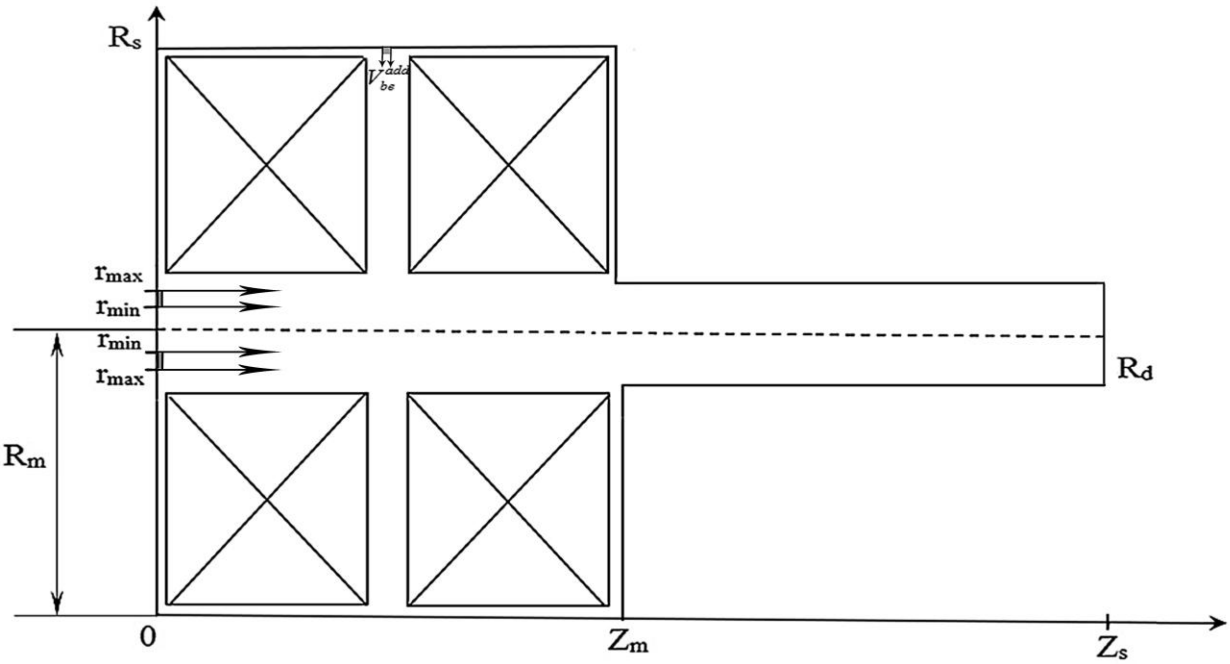

Fig. 1. Cross-section of the LIA experimental model along z by the xz-plane

Fig. 2 shows dependence of the longitudinal component of the magnetic field induction B_{0z} on the longitudinal coordinate z. The curves, illustrated in Fig. 2, are shown in the reference points: $x_1 = 0.465$ m, $y_1 = 0.515$ m, $x_2 = 0.47$ m, $y_2 = 0.505$ m, $x_3 = 0.47$ m, $y_3 = 0.51$ m, which are selected to illustrate the various characteristics of the problem on the outer and inner edges, in the center of the original location of the ion and the main electron beams.

We have been considered the following variants: 1) DG radius $R_d = 0.075$ m 2) the additional electron beam injector is shifted to the left on the 0.001 m (compared with the case 1) so that the left edge of the injector coincides with the magneto-insulated gap center, moreover DG radius $R_d = 0.05$ m.

In both cases injection time of the additional electron beam was selected in accordance with other parameters of the beams and system.

At the initial time HCIB and the main electron beam are injected. Since the velocity of the main electron beam in ≈3.7 times higher the speed of the CIB, it overtakes the ion beam, electron beam velocity decreases, and its density increases, resulting in partial charge compensation of HCIB. In the center of the magneto-isolated gap the main electron beam is locked because of undercompensation and trapped magnetic field configuration. On expiry 2 ns in the first case (2.5 ns in the second case) after the start of the HCIB and main electron beam injection the additional electron beam is injected. Location and time of the additional electron beam injection was chosen in such a way that he had met with the HCIB in the second half of the magneto-isolated gap.

Fig. 3 shows a longitudinal current dependence of the additional electron beam on the longitudinal coordinate for two studied variants. It is seen that in the first case, when the radius of the DG $R_d = 0.075$ m, the additional electron beam current is almost uniform along the system and is equal to the original CIB current (see Fig. 3,a), i. e. current compensation of the ion beam is realized. In the second case, DG radius is less than in the first variant (R_d = 0.05 m), so a portion of the additional beam is lost on the walls of magneto-isolated and drift gaps, as a result, the electron current decreases up to ≈ 6 kA at the end of the system (see Fig. 3,b).

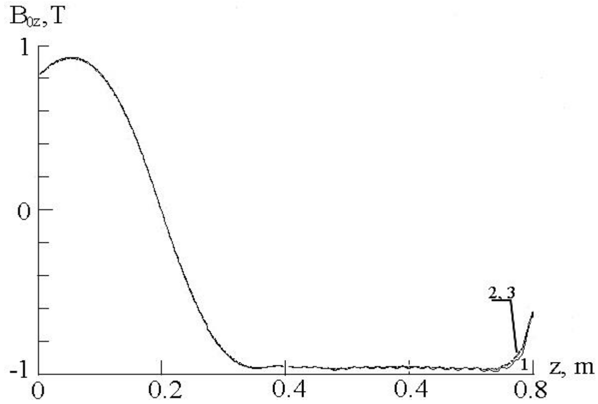

Fig. 2. Dependence of longitudinal component of external magnetic field induction on the longitudinal coordinate z in different points on x, y

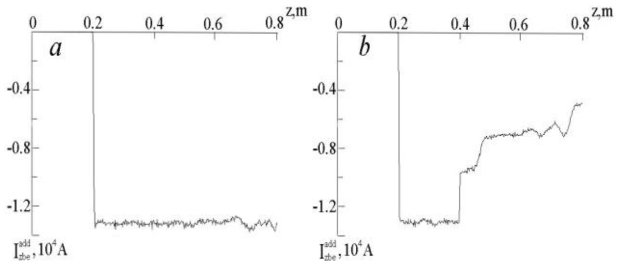

Fig. 3. Dependence of the longitudinal component of the addition electron beam current on the longitudinal coordinate z: first variant (a), second variant (b)

In the first variant the additional electron beam carries the current and partially charge compensation of the HCIB in the second half of magneto-isolated gap and in the DG. But, since the maximum radius of the additional electron beam, moving along the system, is higher about two times than the initial radius of the CIB, and also it has a 3.6 times lower density, the ion beam is strongly undercompensated by charge in the first half of DG already. As a result, CIB diverges radially, and part of it remains on the walls of the DG, that's why the ion current decreases considerably, particularly at the exit of the system (Fig. 4,a). In the second case the situation is similar, but since the DG radius is smaller in this case and the additional electron beam accomplishes current and charge compensation only partially, a part of the CIB is lost not only on the walls of the DG, but also the magneto-isolated gap. Therefore, the CIB current at the beginning of the drift gap sharply falls by a third, and then decreases almost linearly along the system (Fig. 4,b).

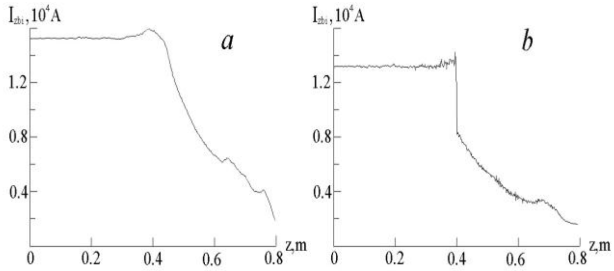

Fig. 4. Dependence of the longitudinal component of the ion beam current on the longitudinal coordinate z: first variant (a), second variant (b)

Because of CIB undercompensation in both cases the energy of the ion beam is reduced at the end of magneto-isolated gap (Fig. 5). On average, HCIB energy remains close to the original, except for the minimum at the end of the magneto-isolated gap and accelerated beam head at the DG end. It is seen, that in the second variant, CIB slows down less than in the first.

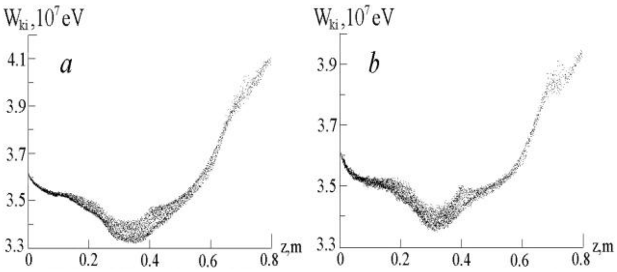

Fig. 5. Dependence of the ion beam kinetic energy on the longitudinal coordinate z: first variant (a), second variant (b)

CONCLUSIONS

In this paper we have studied the dynamics of the compensated ion beam transportation in the external magnetic field in magneto-isolated and drift gaps of LIA with a collective focusing.

Two variants of the DG geometry and the HCIB compensation by the additional electron beam, injected radially in the magneto-isolated gap, have been considered. It is shown that at the chosen value and configuration of the external magnetic field, with the help of programmed injection of the additional electron beam, accompanying the CIB in the second half of the system, it is possible to accomplish almost a full current and partial charge compensation of the CIB.

It should be noted that in the second case, part of the electron beam current is lost because of smaller DG radius, but due to optimization of its injection, CIB current at the exit of the system is the same as in the first case. Moreover minimum kinetic energy of the CIB in the second variant is smaller than in the first.

We have selected the parameters of the additional electron beam injection radially, at which its transportation is realized in such a way that it accompanies the CIB in the most part of the system. Since at these parameters of the additional electron beam injection the CIB at the exit of the system does not satisfy all requirements of HIF, further optimization of the ion beam compensation is necessary. As shown earlier, the only electron beam injection in the DG is insufficient [7], i. e. another electron beam injection from the end of the DG towards the CIB, is needed. Therefore, our future research will focus on optimization the injection of the additional electron beam radially in a magneto-insulated gap and counter electron injection in the DG for CIB compensation.

It should be noted, that even in the absence of counter electron beam CIB parameters are useful for a number of important technological applications at the exit of the system.

REFERENCES

1. V.I. Karas', V.V. Mukhin, A.M. Naboka. About compensated ion acceleration in magnetoisolated systems // *Sov. J. Plasma Phys.* 1987, v. 13, № 4, p. 281-283.
2. V. Batishchev, V.I. Golota, V.I. Karas', et al. Linear induction accelerator of charge-compensated ion beams for ICF // *Plasma Phys. Rep.*1993, v. 19**,** № 5 **,** p. 611-646.
3. N.G. Belova, V.I. Karas', Yu.S. Sigov. Numerical simulation of charged particle beam dynamics in axial symmetric magnetic field // *Sov. J. Plasma Phys*. 1990, v. 16, № 2, p. 115-121.
4. N.G. Belova, V.I. Karas'. Optimization of High-Current Ion Beam Acceleration and Charge Compensation in Two-Cusps of Induction Linac // *Plasma Phys. Rep.* 1995, v. 21, № 12, p. 1005-1013.
5. V.I. Karas', N.G. Belova. Acceleration and stability of high-current ion beams in two accelerating gaps of a linear induction accelerator // *Plasma Phys. Rep.* 1997, v. 23, № 4, p. 328-331.
6. V.I. Karas', O.V. Manuilenko, V.P. Tarakanov, and O.V. Fedorovskaya. Acceleration and stability of a high-current ion beam in induction fields // *Plasma Phys. Rep.* 2013, v. 39, № 3, p. 209-225.
7. V.I. Karas', O. V. Manuilenko, E.A. Kornilov, V.P. Tarakanov, O.V. Fedorovskaya. Transportation of High-Current Ion and Electron Beams in the Accelerator Drift Gap in the Presence of an Additional Electron Background // *Plasma Phys. Rep.* v. 41, № 12, p. 1108-1126, 2015.
8. V.I. Karas', O.V. Manuilenko, E.A. Kornilov, V.P. Tarakanov, O.V. Fedorovskaya. Dynamics of the high-current ion beam in a section of the linear induction accelerator // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2015, № 6(100), p. 52-55.
9. V.P. Tarakanov. User's Manual for Code KARAT // *Springfield VA: Berkley Research Associates Inc.*1992, p. 137.

Article received 12.10.2016

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ТРАНСПОРТИРОВКИ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА С ДОПОЛНИТЕЛЬНОЙ ИНЖЕКЦИЕЙ ЭЛЕКТРОННЫХ ПУЧКОВ В ДРЕЙФОВОМ И УСКОРЯЮЩЕМ ПРОМЕЖУТКАХ ЛИУ

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

Исследована динамика сильноточного ионного пучка (СИП) в системе, состоящей из магнитоизолированного ускоряющего зазора и дрейфового промежутка экспериментальной модели линейного индукционного ускорителя. Проведена оптимизация геометрии магнитного поля, места и времени инжекции дополнительного электронного пучка, а также его поперечного размера. Показано, что при установленных параметрах пучков, внешнего магнитного поля, инжекции основного и дополнительного электронных пучков удаётся скомпенсировать СИП (токи СИП и дополнительного электронного пучка практически равны первоначальным значениям и равны между собой) так, что на выходе из системы его параметры остаются пригодными для ряда важных технологических приложений.

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ТРАНСПОРТУВАННЯ ПОТУЖНОСТРУМОВОГО ІОННОГО ПУЧКА З ДОДАТКОВОЮ ИНЖЕКЦІЄЮ ЕЛЕКТРОННИХ ПУЧКІВ У ДРЕЙФОВОМУ І ПРИСКОРЮЮЧОМУ ПРОМІЖКАХ ЛІУ

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

Досліджено динаміку сильнострумового іонного пучка (СІП) в системі, що складається з магнітоізольованого прискорюючого зазору та дрейфового проміжку експериментальної моделі лінійного індукційного прискорювача. Проведена оптимізація геометрії магнітного поля, місця і часу інжекції додаткового електронного пучка, а також його поперечного розміру. Показано, що при встановлених параметрах пучків, зовнішнього магнітного поля, інжекції основного і додаткового електронних пучків вдається компенсувати СІП (струми СІП і додаткового електронного пучка практично дорівнюють первинним значенням та є рівними між собою) так, що на виході з системи його параметри залишаються придатними для ряду важливих технологічних застосувань.