# NUMERICAL SIMULATION OF HIGH-CURRENT ION BEAM TRANSPORTATION AT THE PRESENCE OF COMPENSATING ELECTRON BEAMS IN A LIA SECTION

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Transportation of a high-current ion beam (HCIB) with various currents was studied in the presence of accompanying and additional electron beams' injection in the linear induction accelerator (LIA) section. The investigations were carried out by means three-dimensional numerical simulation within the framework of the complete Vlasov-Maxwell system of equations. The parameters of the system and beams have been optimized in so way, that the ion beam quality remains acceptable for a number of important technological applications at the exit of the LIA section.

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## INTRODUCTION

Heavy ion fusion, radiation material science, processing of constructional and many other materials are important technological applications, for the effective realization of which heavy ion beams can be used [1, 2]. Such beams are able to obtain in LIA. LIA with collective focusing of a high-current tubular ion beam, proposed in [3, 4], can be used for the above purposes.

The mechanism charge and current compensation of an ion beam by an electron beam in an axisymmetric accelerating gap was investigated in [5 - 7]. In paper [7], the acceleration of the compensated ion beam (CIB) in two magneto-insulated gaps was considered. It was shown that the injection of thermal electrons into the drift gaps allowed compensating charge of the high-current ion beam, ensuring its high quality.

In paper [8], the HCIB transport dynamics in the LIA drift gap, where the external magnetic field was created by coils, has been studied. Several variants of the ion beam charge compensation have been considered. It is shown that proposed parameters of the ion beam compensation allow the ion beam to be the most effectively compensated for the charge, leading to the basic CIB parameters' keeping. It is shown that in the case of specially chosen parameters for additional electrons' injection, the ion beam current at the exit from the drift gap is practically equal to the initial one, and CIB remains monoenergetic.

The particles dynamics in the LIA section in the presence of an external magnetic field has been studied. The ion beam current compensation was carried out by an electron beam [9]. It is shown that with optimized electron injection towards the main electron and ion beams, the HCIB current is almost equal to the initial one at the exit from the LIA section. At the same time, CIB, acquiring energy in the accelerating gap, remains monoenergetic.

In [10], the HCIB dynamics in magneto-isolated and drift gaps has been studied. It is shown that at a larger drift gap radius, there are practically no losses, both of the compensating additional beam electrons, and of the HCIB ions. It is shown that, both at a smaller and at a larger drift gap radius, even in the absence of opposite directed electrons injection, the CIB quality at the exit of the system remains acceptable for a lot of technological applications.

In this paper we have investigated the HCIB transportation in the presence of compensating basic electron beam and additional electron beam in the LIA experimental model section. The dynamics of the CIB with different current has been considered. It is shown that with a smaller current of the CIB, its quality at the exit from LIA, due to a smaller space charge, is higher than in the case of a larger HCIB current. It is shown, that for chosen parameters of the HCIB and the additional electron beam, the ion beam remains suitable for scientific research, ion implantation and radiation material science.

## SIMULATIONS RESULTS

The electron and ion beams transport dynamics has been studied numerically by means a powerful 3-dimensional code KARAT [11]. KARAT is fully electromagnetic code on the basis of the macroparticles method. It is intended for solving non-stationary electrodynamic problems, having complex geometry and including dynamics, in the general case, of relativistic particles (electrons, ions, neutrals).

Fig. 1 shows a section through the middle and along the investigated section (longitudinal coordinate $z$), consisting of LIA magneto-isolated and drift gaps. The length of the magneto-isolated gap is $z_m = 0.4$ m, the length of the drift gap is 0.4 m, the length of the system is $z_s = 0.8$ m. The radius of the magneto-isolated gap is $R_m = 0.5$ m, and the drift gap radius is $R_d = 0.1$ m. The axis of the system symmetry is shown in Fig. 1 by dashed line, passing through the point $x = 0.5$ m, $y = 0.5$ m.

At the beginning of the magneto-isolated gap (see on the left, Fig. 1) the ion beam with density $n_{bi} \approx 7 \cdot 10^{17}\,\mathrm{m}^{-3}$ ($I_{zi}$ = 13.2 kA) in the first variant, $n_{bi} \approx 3.6 \cdot 10^{17}\,\mathrm{m}^{-3}$ ($I_{zi}$ = 6.6 kA) in the second case, and the speed $V_{bi} = 0.27\,c$ and the main electron beam, compensating the HCIB current, with a density of $n_{be} = 2 \cdot 10^{17}\,\mathrm{m}^{-3}$ and a velocity $V_{be} = 0.99\,c$, where $c$ is the speed of light, are injected at the initial time. The direction of both beams motion is shown in Fig. 1 on the left. The internal beam size $r_{min}$ = 0.028 m, outer one $r_{min}$ = 0.035 m. The beams are axially symmetric relatively the dashed straight line only at the initial time moment (see Fig. 1). Fig. 1 also shows the location of the injection along the radius of the additional electron beam with the velocity $V_{eb}^{add} = 0.99\ c$ into the magneto-insulated gap. The additional electron beam injector has a thickness of 0.003 m. The injection location has been chosen in the way, that the additional electron beam, moving along the corresponding force magnetic lines, would fall on the initial cross-section of the main electron beam and CIB in the second half of magneto-isolated gap and would accompany it to the system end.

The external magnetic field in the magneto-isolated gap is created by coils with counter currents and has a cusp configuration. Coils, placed in the magneto-insolated gap have turns, both in the transverse direction and in the longitudinal one. In the drift gap, the magnetic field is formed by coils of the same size and radius with the same current in them, so the magnetic induction along the gap practically does not change, and the field is uniform.

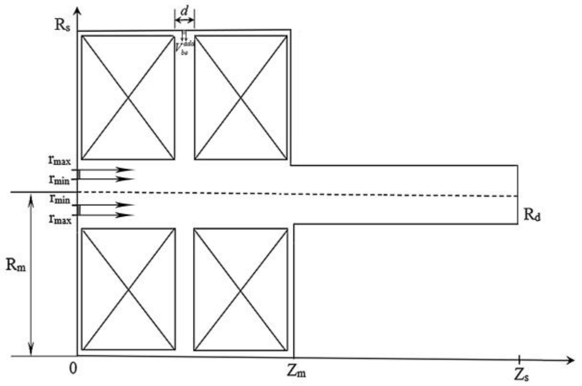

*Fig. 1. Cross-section of the LIA experimental model along z by the xz-plane*

The dependence of the longitudinal component of the magnetic field induction $B_{0z}$ on the longitudinal coordinate *z* is show on Fig. 2. The curves in Fig. 2, are shown at 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, $z_3$= 0.55 m, which are chosen to illustrate various characteristics of the problem at the center, at the outer and inner edges of the initial location of the ion and main electron beams.

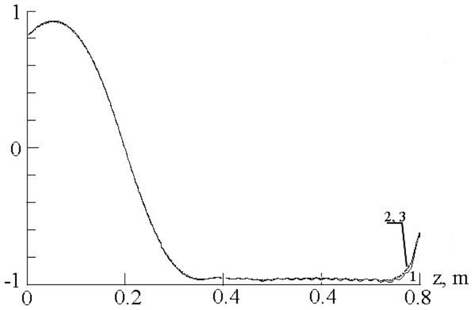

*Fig. 2. Dependence of longitudinal component of external magnetic field induction on the longitudinal coordinate z in different points on x, y*

In the first variant, when the HCIB density is higher, the ion beam current along the system remains close to the initial one practically to the middle of the drift gap (Fig. 3,a). In the second half of the drift gap, because of incomplete charge compensation, the HCIB significantly diverges so that part of the particles goes on the walls, as a result of that the current strength decreases significantly and reaches about 7.5 kA at the exit from the section.

In the second case, the HCIB density is two times smaller, so it diverges in the drift gap not as significantly as in the first case, so that the current at the exit from the system is close to the initial one – about 6.5 kA (Fig. 3,b). Thus, at the exit from the section ion beam current in the first case decreases almost twofold, and in the second one – by 100 A.

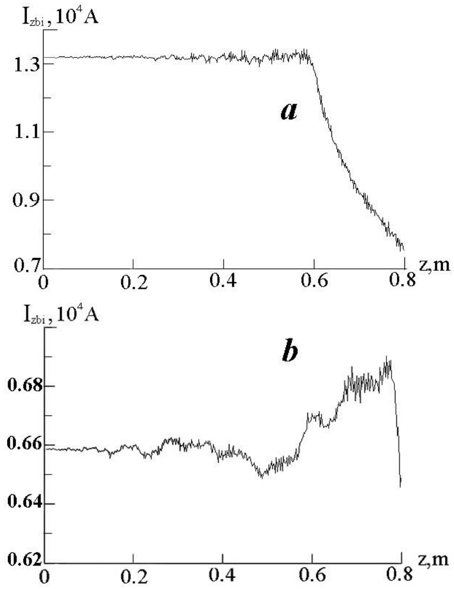

*Fig. 3. Dependence of the longitudinal component of the ion beam current on the longitudinal coordinate z: first variant (a); second variant (b)*

The dependence of CIB kinetic energy on the longitudinal coordinate is illustrated on Fig. 4. It is seen, that in both cases there are areas of acceleration and deceleration of the ion beam, which are associated with the HCIB incomplete charge compensation.

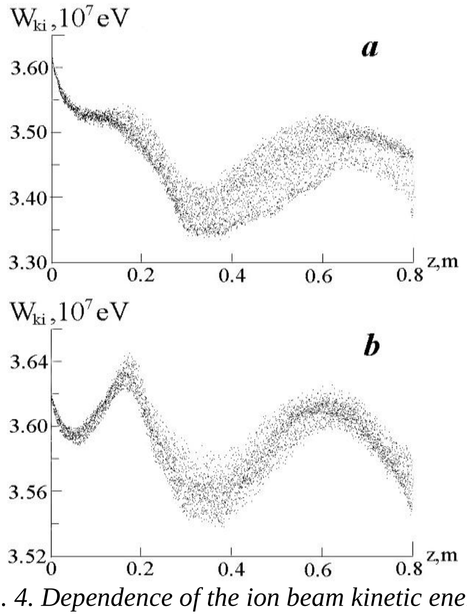

*Fig. 4. Dependence of the ion beam kinetic energy on the longitudinal coordinate z: first variant (a); second variant (b)*

The minimum of the ion beam kinetic energy has appeared at the end of the magneto-isolated gap, where the system dimensions are quite different – the radius of the magneto-isolated gap is 5 times larger than the drift gap radius (Fig. 1). In the case of the higher ion beam density, the energy minimum reaches 33.5 MeV (Fig. 4,a), whereas in the second one it reaches 35.4 MeV (Fig. 4,b). At the exit from the system, the HCIB has kinetic energy in the first case 34.6 MeV, and in the second case it is 35.6 MeV, i.e. the energy losses of HCIB are: in the first case about 4%, in the second – no more than 2%.

## CONCLUSIONS

In this paper the dynamics of the high-current ion beam transportation in the presence of an external magnetic field in the section of LIA with collective focusing has been studied.

Two cases of the HCIB transportation, when its density is: 1) $n_{bi} \approx 7 \cdot 10^{17}\,\mathrm{m}^{-3}$, 2) $n_{bi} \approx 3.6 \cdot 10^{17}\,\mathrm{m}^{-3}$ have been considered. It is shown that HCIB in both cases noticeably slowed down at the end of the magneto-insolated gap, and then accelerated to practically the initial energy, and the HCIB deceleration again occurred at the end of the drift gap. It is shown that, at the exit from the system, CIB kinetic energy in the first case is less than the initial energy (36.2 MeV) by 1.6 MeV, and in the second case – by 0.6 MeV. Moreover, HCIB with higher density because of incomplete charge compensation diverges significantly in the transverse direction in the second half of the drift gap, losing particles on the system walls. Therefore, the HCIB current in the first case decreases practically twofold, and in the second case it decreases by 2% (in 1.02 times). Thus, in the case of HCIB lower density at the chosen parameters of the compensating electron beams and the system, the ion beam has the current and the energy close to the initial ones at the exit from the LIA section. Consequently, HCIB with these parameters remains acceptable for a number of important technological applications. It should be noted that, in spite of less acceptable parameters of ion beam with higher density at the exit from the system, it can be used for ion implantation, studying and processing structural materials.

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## ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ТРАНСПОРТИРОВКИ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА ПРИ НАЛИЧИИ КОМПЕНСИРУЮЩИХ ЭЛЕКТРОННЫХ ПУЧКОВ В СЕКЦИИ ЛИУ

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

Изучена транспортировка сильноточного ионного пучка (СИП) с различными токами при наличии инжекции сопровождающего и дополнительного электронных пучков в секции линейного индукционного ускорителя (ЛИУ). Исследования проводились с помощью трехмерного численного моделирования в рамках полной системы уравнений Власова-Максвелла. Параметры системы и пучков оптимизированы таким образом, что на выходе из секции ЛИУ качество ионного пучка остается приемлемым для ряда важных технологических приложений.

## ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ТРАНСПОРТУВАННЯ СИЛЬНОСТРУМОВОГО ІОННОГО ПУЧКА ЗА НАЯВНОСТІ КОМПЕНСУЮЧИХ ЕЛЕКТРОННИХ ПУЧКІВ У СЕКЦІЇ ЛІП

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Вивчено транспортування сильнострумового іонного пучка (СІП) з різними струмами при наявності інжекції супроводжуючого та додаткового електронних пучків у секції лінійного індукційного прискорювача (ЛІП). Дослідження проводилися за допомогою тривимірного чисельного моделювання в рамках повної системи рівнянь Власова-Максвелла. Параметри системи і пучків оптимізовані таким чином, що на виході з секції ЛІП якість іонного пучка залишається прийнятною для низки важливих технологічних застосувань.