HIGH-CURRENT ION BEAM COMPENSATION IN A SECTION OF AN INDUCTION LINAC

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The particle transport dynamics in the section of a linear induction accelerator (LIA) has been studied. The system and beams parameters (the magnetic field magnitude, the system dimensions, the beams parameters), which allowed compensating the ion beam in the entire LIA section are found. It is shown, that the high-current ion beam (HCIB) at the system output can be used in many technological applications.

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

INTRODUCTION

It is known that a linear induction accelerator is one of the most promising drivers that can produce high-energy beams for heavy ion fusion (HIF), surface modification of various materials, radiation material science and other important technological applications. On the one hand, LIA makes it possible to obtain high-current heavy ion beams, on the other – it is more competitive from an economic standpoint than some other types of drivers. Therefore, a number of countries have been developing and designing LIA with various methods of a high-current ion beam compensation (see, for example, [1 - 4]). In Ukraine, accelerators of this type are also being investigated, for instance, the LIA with collective focusing of a tubular HCIB, suggested at the National Science Center "Kharkov Institute of Physics and Technology" of the National Academy of Sciences of Ukraine [5, 6]. This method of focusing allows creating a compact accelerator with HCIB, which can be used in the above-mentioned applications.

The charge and current compensation of the ion beam by an electron beam in an axisymmetric accelerating gap was investigated in Refs [7 - 9]. In [9] the acceleration of the compensated ion beam (CIB) in two cusps had been also considered. It is shown that the thermal electrons injection into the accelerator drift gaps makes it possible to carry out the HCIB charge compensation, ensuring the ion beam high quality.

Previously [10] the HCIB stability relatively dangerous filamentation instability in the LIA drift gap had been investigated, and it was demonstrated that at the presence of a stabilizing external longitudinal magnetic field, despite the instability development, the HCIB quality at the LIA exit satisfies the requirements to the driver beam for HIF.

In [11], the particles dynamics in the LIA drift gap at the presence of an external magnetic field, which had the trap configuration, has been numerically studied. The ion beam current compensation has been occurred by an electron beam.

The ion beam transport dynamics in the external magnetic field in the drift gap of the LIA with collective focusing has been studied. The variants of the HCIB charge compensation in the drift gap are considered. The additional electrons are injected from the right boundary of the drift gap to ensure the CIB charge compensation after one time of the ion flight through the system.

It is found that the start and the duration of additional electrons injection, as well as their speed, are of great importance for HCIB homogeneous compensation. It is shown that, in the most acceptable variant of HCIB compensation, the ion beam current at the exit of the drift gap was close to the original one, and since the electron beam also retained its current, the ion beam current has been practically compensated at the exit of the system.

The HCIB compensation variant, found in Ref. [12] allows maintaining the CIB quality, required for HIF, but further improvement of the compensation method is required to reduce the HCIB energy dissipation and angular divergence.

In [13], the HCIB transport and acceleration in a LIA magnetically insulated gap have been studied. The beams' and system parameters, at which transport and acceleration of the HCIB with keeping its current, density, and cross section close to the original ones are realized in the magnetically insulated gap, have been found. It is shown that the HICB accelerated almost uniformly, while the ion beam quality remained rather high: monoenergeticity and the cross-section of the CIB were kept at the exit of the magnetically insulated gap.

The ion beam transportation and acceleration in a system consisting of a magnetically insulated gap and two drift ones have been studied [14]. It is shown that the HCIB parameters at the exit from the LIA section in the presence of: a magnetic field, the accompanying electron beam injection, programmed injection of the additional electron beam, remained acceptable for a number of important technological applications.

The ion and electron beams dynamics in the system with parameters of the LIA section experimental model has been considered in [15, 16]. It is shown that, because of the significant difference in the transverse dimensions of the magnetically insulated clearance and the drift gaps, it is possible to inject the additional electron beam, carried out the HCIB compensation, only for certain beam densities. Therefore, at high CIB densities, the ion beam transverse dimensions and energy spread increase at the exit of the system. It is ascertained, that (at found parameters of the beams and system) it was managed to maintain the HCIB quality acceptable for important technological applications, at the LIA section exit [17].

In this paper, the particles dynamics in the LIA section has been investigated. The transportation of the HCIB with various densities in the external magnetic field presence in this system has been studied. Different HCIB compensation methods have been offered. It is shown that for the ion beam with enough high current, its compensation by the main electron beam accompanying HCIB in the entire LIA section is the most effective.

1. HCIB TRANSPORTATION IN MAGNETICALLY ISOLATED AND DRIFT GAPS

A powerful 3-dimensional code KARAT [18], allowing solving complex problems, was used for a numerical study of the beam transportation dynamics. KARAT is fully electromagnetic code on the basis of the method of macroparticles. 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).

In this section, the HCIB transportation in the LIA section is investigated by the 2.5-dimensional modeling in the rz-geometry. The numerical model has the following parameters: 10 macroparticles per cell, the maximum number of cells along r I_{max} = 200, along z – J_{max} = 2400. The conditions, ensuring the numerical stability of calculations [19] are fulfilled.

The geometry of the problem, where r_L is the transverse and z_L is the longitudinal dimensions of the system, r_{min} and r_{max} are the internal and external radii of the ion beam and electron one, carrying out the HCIB charge compensation at the initial moment of time, and also the coils creating the cusp magnetic field in the magnetically isolated clearance and the longitudinal homogeneous field of 3.6 T in the drift gap is shown in Fig. 1. The additional electron beam injection place is also shown.

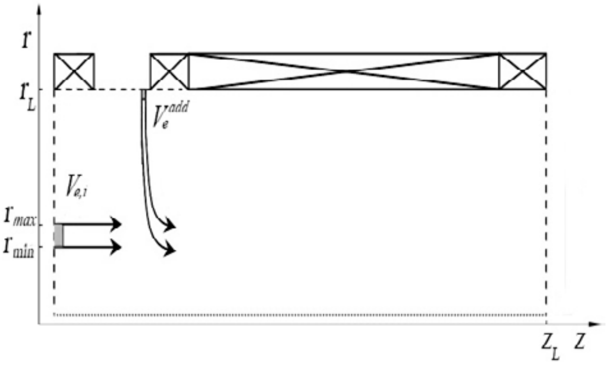

Fig. 1. Geometry of the computational area, the beam injection regions

The section has the form of a cylinder with a radius of 0.1 m and a length of 0.48 m.

There is an axially symmetric geometry of the beams and the system along the z axis, indicated in Fig. 1 by the dotted line. Internal radii of tubular beams r_{min} = 0.029 m, external – r_{max} = 0.035 m.

Two cases of the HCIB transportation have been considered: 1) at the initial instant of time, on the right, ion and electron beams with density $n_{bi} = n_{be} = 3.65\cdot10^{17}$ m^{-3} are injected 2) at the initial instant of time, on the right, ion and electron beams with density $n_{bi} = n_{be} = 2.1\cdot10^{17}$ m^{-3} are injected. In both cases, the HCIB velocity is V_{bi} = 0.27 c, and the electron beam velocity V_{be} = 0.99 c, where c is the speed of light. An additional electron beam injected on the radius has the same velocity ($V_{be}^{add} = V_{be}$) as the main electron beam and the same density (at the CIB cross section), like the beams have, for the two variants, respectively.

The main electron beam performs the HCIB compensation only in the first part of the magnetically isolated gap. Then the programmed injection of an additional electron beam, which accompanies the CIB in practically the entire accelerator section, is carried out into the second part of the magnetically insulated gap. In this case, the injection place and time, as well as the additional electron beam width have been chosen in such a way that it would meet with the HCIB in the second part of the magnetically insulated gap and at the same time fall into on the CIB cross-section. We managed to significantly reduce the HCIB divergence due to the optimal choice of the beam parameters and the additional electron beam injection (Fig. 2,c,d).

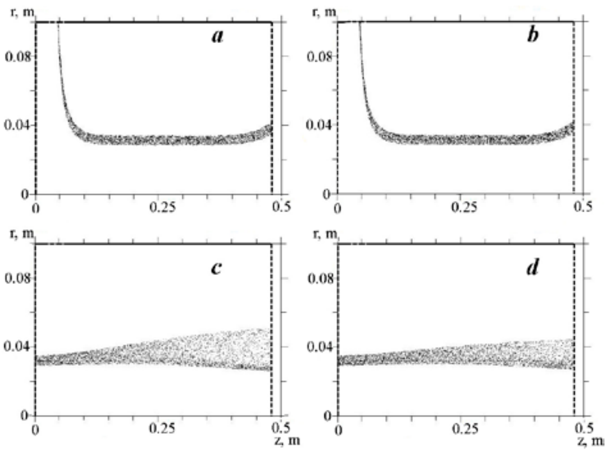

Fig. 2. rz-space of electron (a, b) and ion (c, d) beams after 2 τ; (a, c) – the first variant; (b, d) – the second variant

As can be seen from Fig. 2, the additional electron beam cross section remains close to the initial ion beam transversal dimension (see Fig. 2,a,b), except for the system end, where the coil magnetic field configuration and magnitude change noticeably. Since an ideal match between the HCIB and the additional electron beam is not managed to achieve, the CIB has a divergence in the transverse direction, especially in the first variant (see Fig. 2,c), where the HCIB density is greater. In the second variant, the ion beam divergence at the exit from the section is small (see Fig. 2,d). It should be noted that in both cases the CIB at the exit from the section keeps the cross section close to the original one, and the ion density outside the cross section is rather small.

After two times of the ion flight through the system τ the additional electron beam current didn’t change along the entire section, as can be seen from Fig. 3. In turn, the ion beam current at the section output is also close to the original one in two variants, and the amplitude of current oscillations in the system second part varies within 1% of the ion current initial value.

The HCIB transportation dynamics is shown in Fig. 4. It can be seen that in both cases CIB accelerated at the beginning of the section, and then its energy practically did not change. In the first variant, the HCIB energy is greater than the original energy (36.2 MeV) by 1.1 MeV (see Fig. 4,a), and in the second variant – by 0.6 MeV (see Fig. 4,b), i. e. the ion kinetic energy at the output of the system has varied insignificantly.

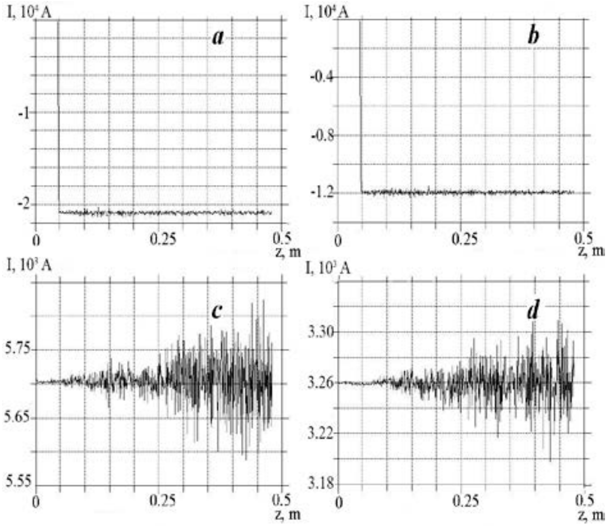

Fig. 3. The longitudinal component of the current for the electron (a, b) and ion (c, d) beams vs the longitudinal coordinate z after 2 τ; (a, c) – the first variant; (b, d) – the second variant

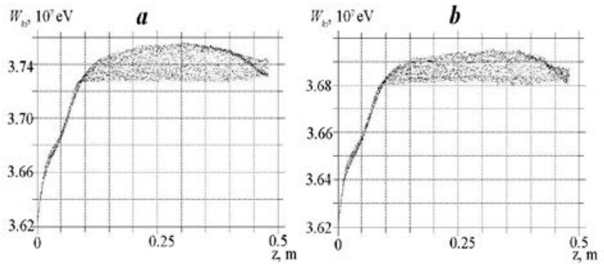

Fig. 4. Dependence of the HCIB kinetic energy on the longitudinal coordinate z after 2 τ; (a) – the first variant; (b) – the second variant

2. THE HCIB TRANSPORTATION IN MAGNETO-ISOLATED AND DRIFT GAPS

In this section we present the results of 2.5-dimensional modeling in the rz-geometry of the HCIB transportation in the LIA section, consisting of two magnetically insulated clearances and a drift gap. The simulations have been carried out by means of 3D-code KARAT. The numerical model has the following parameters: 10 macroparticles per cell, the maximum number of cells along *r* $I_{max} = 200$, along *z* – $J_{max} = 2800$. The conditions, ensuring the numerical stability of calculations [19] are fulfilled.

The geometry of the problem, where r_L is the transverse and z_L is the longitudinal dimensions of the system, r_{min} and r_{max} are the internal and external radii of the ion beam and electron one, carrying out the HCIB current compensation at the initial moment of time, and also the coils creating the cusp magnetic field in the magnetically isolated clearances and the longitudinal homogeneous field of 3.6 T in the drift gap is shown in Fig. 5. The additional electron beam injection place is also illustrated.

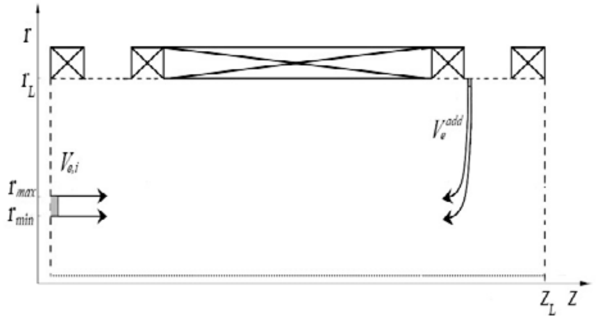

Fig. 5. Geometry of the computational area, the beam injection regions

The section has the form of a cylinder with a radius of 0.1 m and a length of 0.56 m, magnetically insulated clearances have a length of 0.08 m and a drift gap – 0.4 m.

There is an axially symmetric geometry of the beams and the system along the *z* axis, indicated in Fig. 5 by the dotted line. Internal radii of tubular beams r_{min} = 0.029 m, external – r_{max} = 0.035 m. The curves, shown in Fig. 6 and Fig. 8, characterize the particle dynamics at points on the initial HCIB cross-section.

At the initial instant of time, the ion beam with the density $7.33 \cdot 10^{19}$ m^{-3} and the velocity V_{bi} = 0.27 *c* and the main electron beam with the density $n_{be} = 2 \cdot 10^{19}$ m^{-3} and the velocity V_{be} = 0.99 *c* (i.e. the HCIB and the electron beam have the same current density and current strength) are injected on right. Three cases of the HCIB compensation have been considered: 1) only the main electron beam, injected simultaneously with the CIB, is in the section; 2) besides the main electron beam, an additional electron beam is injected into the magnetically insulated gap at the beginning of the system on the LIA section radius, with a speed equal to the main electron beam speed $V_{be}^{add} = V_{be}$ and with the same current (see Fig. 1, first paragraph); 3) the counter-injection on the system radius of the additional electron beam with the same parameters (except for the original radius) as for the main electron beam is implemented in the second magnetically insulated gap (see Fig. 5).

The beams parameters are chosen in such a way that the corresponding self-consistent fields ensure the electron drift through the magnetically isolated gaps [20] (that is, the beams currents are sufficiently high – about 1MA). From Fig. 6 that in all cases the self-consistent electric E_r (see Fig. 6,a,c,e) and magnetic B_θ (see Fig. 6,b,d,f) fields, created by the beams are high enough, that allows the electrons accompany the HCIB not only in the magnetic-insulated gap, but and all along the entire section. In all cases, the electron beam current remains close to the initial value in the most part of the system, and then increases significantly (see Fig. 7,a,c,e), especially in the second (see Fig. 7,c) and the third (see Fig. 7,e) cases, where there is the additional electron beam injection, which hinders the main electron beam transportation. In this case, the additional electron beam by its field partially displaces the main electron beam, leading to the current decrease to zero and breaking the beam into bunches at the end of the LIA section. Naturally, such a dynamics of electrons leads to the HCIB quality decrease. In the first case, when there is no injection of the additional electron beam, the HCIB "holds out" the main electron beam, which compensates the ion beam. This circumstance on the one hand reduces the CIB quality, on the other hand (due to compensation) keeps its current and energy (see Fig. 7,b, Fig. 8,a). Whereas in the presence of an additional accompanying electron beam, regions with significant HCIB undercompensation and overcompensation arise, which leads to an inhomogeneous distribution of the ion beam density and current, up to the current decreasing by almost an order of magnitude at the exit from the section (see Fig. 7,d). In the presence of counter injection of an additional electron beam into the second magnetically insulated gap, the CIB current is also ununiform, but at the output from the system is close to the original current (see Fig. 7,f).

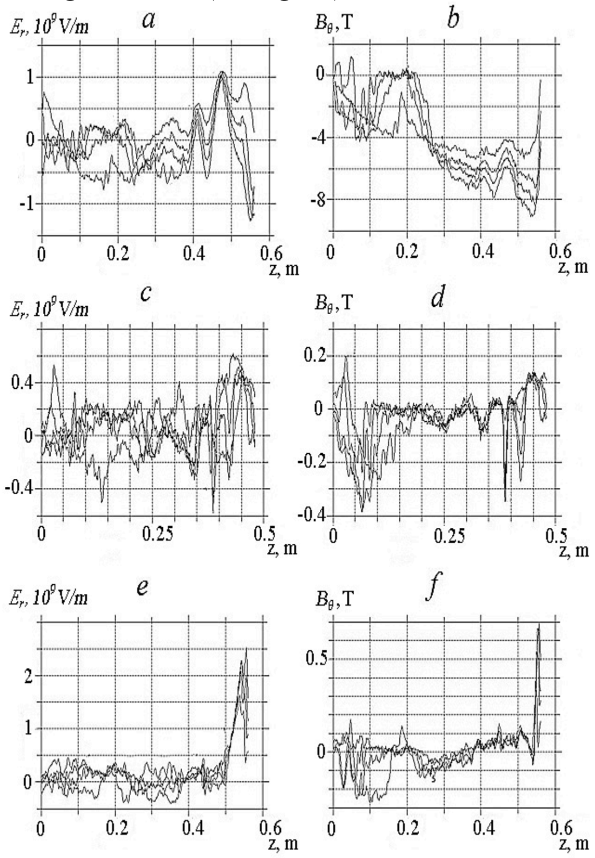

Fig. 6. Dependence of the self-consistent electric E_r (a, c, e) and magnetic B_θ (b, d, f) fields on the longitudinal coordinate z: (a, b,) – the first variant, (c, d) – the second variant, (e, f) – the third variant

The suggested options of the HCIB compensation allow keeping ion beam kinetic energy close to the initial one (see Fig. 8,a,c,e) in the system first part, while at LIA section end the energy spread significantly increases, and the ion bean energy in the first variant (see Fig. 8,a) remains close to the initial, in the second (see Fig. 8,c) and the third (see Fig. 8,e) – decreases almost to zero.

It should be noted, it is not managed to achieve the ion beam full compensation because of the nonuniformity of the HCIB and electron beams density distribution, as can be seen from the total particle density in the system (see Fig. 8,b,d,f). At the same time, in the first variant, it has been managed to compensate HCIB almost in the entire section by 85%. While in the second and third cases, compensation is more inhomogeneous – there are regions with a high density of not only negative but also positive particles (see Fig. 8,d,f).

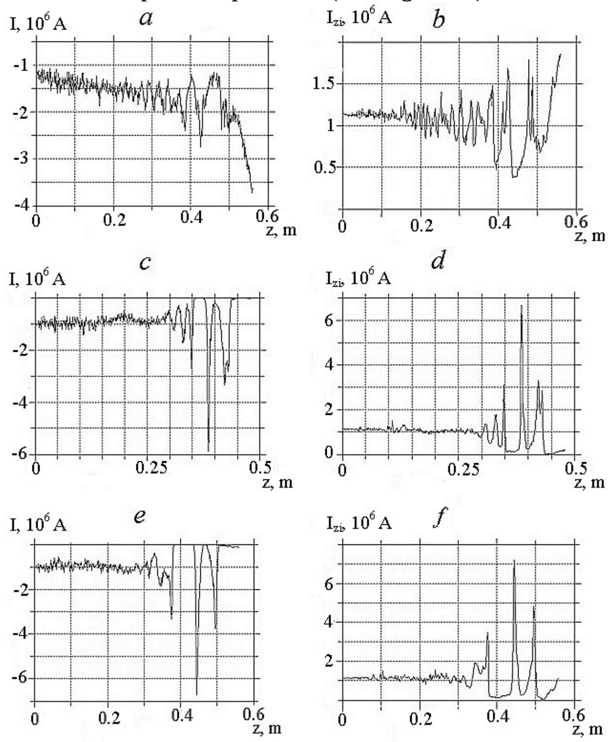

Fig. 7. The longitudinal component of the current for the electron (a, c, e) and ion (b, d, f) beams vs the longitudinal coordinate z after 2 τ; (a, b) – the first variant, (c, d) – the second variant; (e, f) - the third variant

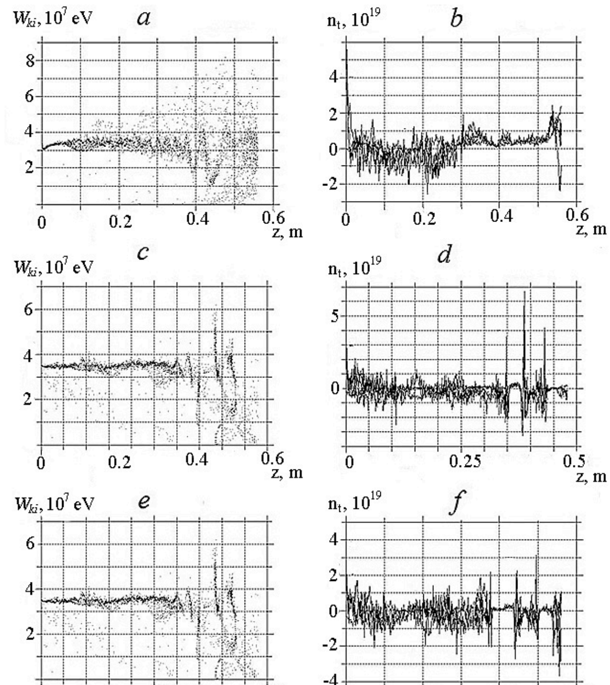

Fig. 8. Dependence of the HCIB kinetic energy W_{ki} (a, c, e) and total particle density (b, d, f) on the longitudinal coordinate z after 2 τ; (a, b,) – the first variant; (c, d) – the second variant, (e, f) – the third variant

CONCLUSIONS

In this paper, the ion beam transportation dynamics with various CIB densities in the LIA section at the presence of an external magnetic field has been studied. In the second section, the HCIB compensation in the first part of the magnetically isolated gap is carried out by an accompanying electron beam injected simultaneously with the ion beam, and in the rest part of the system by an additional electron beam. It is shown that with the selected parameters of the system, external magnetic field and beams, it is possible to transport the ion beam in the LIA section. The parameters of the additional electron beam and its injection, at which it is possible to compensate the HCIB so that it can be used at the exit of the system in a number of important technological applications, have been found. It is shown that at a lower ion beam density, it not only maintains current and energy close to the initial, but also practically does not diverge in the transverse direction.

In the third work section, the following variants of HCIB compensation in the LIA section are considered: 1) by the main electron beam, injected simultaneously with the ion beam; 2) besides the main electron beam, there is an additional electron beam injected along the HCIB direction into the first magnetically insulated gap; 3) besides the main electron beam, there is an additional electron beam injected along the radius towards the HCIB in the second magnetic-isolated gap.

It is shown that for a sufficiently high ion beam (about 1 MA), the drift of the compensating beam electrons is realized not only in the magnetically insulated gaps, but also in the drift gap, that allows compensating the HCIB in the entire LIA section. It is shown that in such conditions the CIB “stretches” the compensating electron beam all along the section, which leads to an increase in the energy spread and a slight decrease in the current of the ion beam at the output of the system. Wherein, the additional electron beams injection regardless of the velocity direction and the injection place (the beginning or the end of the system), hinders the main electron beam passage, that is, there is no need for such beam parameters in additional HCIB compensation, which in these cases renders a negative effect on the ion beam.

Thus, due to the selected parameters of the beams and the system, we have been able not only to transport the HCIB with current of 1 MA in the LIA section, but also to keep the ion beam quality high enough (the energy and current at the exit of the system are close to the initial ones).

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Article received 23.05.2018

КОМПЕНСАЦИЯ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В СЕКЦИИ ЛИНЕЙНОГО ИНДУКЦИОННОГО УСКОРИТЕЛЯ

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Изучена динамика транспортировки частиц в секции линейного индукционного ускорителя (ЛИУ). Найдены параметры системы и пучков (величина магнитного поля, размеры системы), при которых осуществляется компенсация ионного пучка вдоль всей секции ЛИУ. Показано, что ионный пучок на выходе из системы может быть использован во многих технологических приложениях.

КОМПЕНСАЦІЯ 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 транспортування часток у секції лінійного індукційного прискорювача (ЛІП). Знайдено параметри системи і пучків (величина магнітного поля, розміри системи), при яких здійснюється компенсація іонного пучка вздовж всієї секції ЛІП. Показано, що іонний пучок на виході з системи може бути використаний в багатьох технологічних додатках.