STABILITY OF THE HIGH-CURRENT ION BEAM IN DRIFT GAP OF LINEAR INDUCTION ACCELERATOR

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The results of numerical simulation of compensated ion beam (CIB) transport with current density 9 MA/m^2 through the drift gap of a linear induction accelerator (LIA) are presented. The CIB stability for the three methods of compensation in the charge of the ion beam in the absence and presence of an external magnetic field is considered. It is shown that in the presence of an external magnetic field instabilities development does not lead to a significant deterioration in the ion beam quality regardless of the compensation way. It is shown, that the most effective addition compensation of the ion beam in charge is applying of self-consistent injection of additional electrons, which leads to the conservation of the CIB parameters, sufficient for its use in heavy-ion inertial fusion (HIF).

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

INTRODUCTION

One of the most perspective methods of obtaining the high-current ion beams for HIF is based on using LIAs. 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 - 3] allows constructing a compact accelerator that can be used as an efficient driver for HIF and also as device for other areas of technology applications. The use of the cusp magnetic field in accelerating gaps of the linac leads to their effective magnetic insulation (suppression of electron current, see [1 - 3]) without the need for an additional central conductor, which greatly simplifies the linac construction. The advantage of such a method of magnetic insulation was noted in [4].

The mechanism of space charge neutralization of the ion beam by an electron beam in the axisymmetric accelerating gap was investigated in [5 - 7].

The possibility of transport and acceleration of a high-current CIB in 1-6 cusps was demonstrated in [8 - 12] by means of numerical simulation within the frame of complete set of Vlasov-Maxwell equations with the help of 2.5-dimensional XOOPIC code [13, 14] that based on the particle-in-cell (PIC) method.

The quasi-linear stage of the instability of plasma with an anisotropic electron distribution function was studied in [15 - 17]. Nonlinear stage of relativistic electron beams filamentation in dense plasmas was numerically simulated by the authors of [18 - 24]. It was shown that, as a rule, the fastest process in the development of instability was not squeeze of the beam as a whole, but rather breaking it into thin threads (the first stage), the scale of which corresponds to the maximum increment of instability, with following compression of the filaments. In the second stage of instability, the compressing filaments are attracted together and coalesce. Simultaneously the transverse temperature increases that ultimately determines the maximum transverse size of the formed filament.

Filamentation instability of the ion beam in the LIA with a collective focusing has been studied theoretically and experimentally in [25 - 30]. It is shown that while the CIB current density is less than the 10 MA/m^2 ion beam remains uniform and development of filamentation instability does not manifest itself.

At current densities in LIA [2, 25] higher 10 MA/m^2 ion beam becomes filament inhomogeneous as the result of the filamentation instability nonlinear stage. In [28 - 30, 31] the development of filamentation instability, both in the absence and in the presence of an external magnetic field, and particles collisions was studied. It is shown that filamentation instability can be suppressed by a strong longitudinal magnetic field in the absence of collisions between all particles in the LIA. Filamentary instability increments were obtained in the presence or in the absence of a magnetic field and collisions between all particles.

In this paper we numerically studied filamentation and high-frequency beam instabilities of CIB in the drift gap, both in the absence and in the presence of an external magnetic field. We examine the cases of CIB transport: in the absence of additional electrons, in the presence of a stationary additional electron injection, in the presence of a self-consistent additional electron injection [32]. It is shown that in the absence of an external longitudinal magnetic field the instabilities development produce a significant degradation of both a compensating electron beam and a compensated ion beam regardless of availability of the additional thermal electrons injection in the drift gap. The presence of an external magnetic field leads to the improvement of the CIB quality. It is found that the self-consistent additional thermal electron injection give the CIB best quality and allows to make efficient transport of CIB through the drift gap at the presence of the external longitudinal magnetic field.

THE SIMULATION RESULTS

For the numerical study of instabilities it is required a powerful code which allows to solve such complex problems. In this section the instabilities are studied using a 3-dimensional code KARAT. KARAT is fully electromagnetic code based on PIC method. It designed for solving of nonstationary electrodynamics problems with complex geometry and including dynamics, in general, relativistic particles (electrons, ions, neutrals) [32].

A real ion linac contains drift gaps with a homogeneous external longitudinal magnetic field alternating with the accelerating gaps, the magnetically insulated accelerating gaps being much shorter (by a factor of 10 - 20) than the drift gaps. Therefore, the study of instabilities in the drift gap makes sense. Consequently, the most severe restrictions on parameters of the electron and ion beams, which ensure the required quality of the ion beam, are expected to be obtained from study of instabilities in the drift gap.

Fig. 1 shows the geometry of the problem, where $z \in [0, z_{LD}]$, z_{LD} is the length of the drift gap. In the simulation: $z_{LD} = 0.5$ m, the transverse dimension of $x_L = 0.1$ m. In the computational region between $x_{min} = 0.042$ m, $x_{max} = 0.06$ m in the initial time are the electrons with density $n_e = 1.9\cdot10^{17}$ m^{-3} and the longitudinal speed $V_{e0} = 0.99$ *c,* where *c* – speed of light, ions with density $n_i = 6.967\cdot10^{17}$ m^{-3} and the longitudinal velocity $V_{i0} = 0.27$ *c*, and thermal electrons with number density $n_{the} = 5.067\cdot10^{17}$ m^{-3} and a temperature of 20 eV. The conditions ensuring current and charge compensation were created in the drift gap, i.e., there were not self-consistent electric and magnetic fields.

During the pulse on the left into the computational region, that is infinite along the *y,* electron and ion beams are continuously injected. The minimum and maximum dimensions of the beams are same: $x_{min} = 0.042$ m, $x_{max} = 0.06$ m, velocities of ion and electron beams are respectively $V_{i0} = 0.27$ c, $V_{e0} = 0.99$ c, the current densities at the time of injection are equal, and their magnitudes 9.02 MA/m^2. Densities of electron and ion beams are $n_e = 1.9\cdot10^{17}$ m^{-3} and $n_i = 6.967\cdot10^{17}$ m^{-3}, respectively. And also the injection of addition electrons with density $n_{the} = 5.067\cdot10^{17}$ m^{-3} and the longitudinal velocity $V_{the} = 0.004$ c can be made.

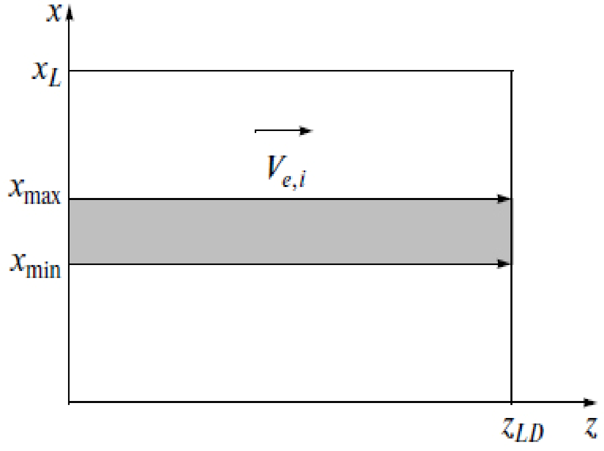

Fig. 1. Area of electron and ion beams (between x_{min} and x_{max}) injection in the computational region ($x_L \times z_{LD}$)

The three cases: 1) the presence of a stationary additional thermal electron injection, 2) the presence of a self-consistent additional thermal electron injection, 3) the absence of the additional electron injection into the system are considered. In all three cases, the transport of the CIB has been studied both in the presence of the uniform longitudinal external magnetic field ($H_0 = 0.23$ T), and in the absence of it.

In the presence of stationary additional electron injection (first case) and external magnetic field the ion beam quality remains quite high, despite the development of filamentation and high-frequency instabilities. The CIB dynamics for this case is detailed in [33]. It is shown that the development of beam instability of the electron beam leads to its modulation (focusing and defocusing regions arise). The arising of transverse magnetic field B_y is because of the electron beam filamentation. The development of these instabilities leads to a significant deterioration in quality of the electron beam, as in the absence (perturbation amplitude is high), and in the presence of an external magnetic field (perturbation amplitude is low). In the presence of an external magnetic field the ion beam is monoenergetic and keeps its parameters are close to the initial one.

The presence of the self-consistent injection of additional thermal electrons in the drift gap (second case) leads to almost complete charge compensation of the ion beam even after the seven electron beam transit times through the system. In this case, unlike the stationary injection (case one), the fresh thermal electrons practically replace the initially loaded thermal electrons.

The absence of thermal electrons injection, leads eventually to a higher CIB undercompensation, than in the cases of injection presence. That results to CIB transverse broadening and increasing of the energy spread of the ion beam. It is clearly seen the difference between the three cases from dependence of the CIB kinetic energy on the longitudinal coordinate *z* after one time of compensating electron beam flight through the system (Fig. 2). It is seen that in the absence of thermal electrons injection and magnetic field, CIB slows down in the beginning, where the thermal electron density is already small (see Fig. 2,a). The presence of the external magnetic field prevents losses of the initially loaded thermal electrons. As the result, the ion beam energy losses are not so significant (see Fig. 2,b). The presence of additional electron injection provides the ion beam compensation, resulting to the absence of “sagging” of ion energy at the beginning (see Fig. 2,c,d). The presence of additional electron self-consistent injection reduces the energy spread of the CIB (see Fig. 2,e,f).

After seven times of compensating electron beam flight through the system, at the presence of external magnetic field ($H_0 = 0.23$ T), in all cases there is a slowing down of the ion beam (Fig. 3). In the case of self-consistent thermal electrons injection, the slowing down of the ion beam takes place at the end of the drift gap (see Fig 3,c). The largest energy dispersion and energy losses occur in the absence of additional thermal electron injection (see Fig. 3,a). The presence of additional electron injection reduces ion beam energy spread, as self-consistent electric fields decrease (see Fig. 3,b). The presence of the self-consistent injection of additional thermal electrons, which completely replace the initially loaded thermal electrons, preserves the CIB is practically uniform over the cross section for the duration of its transport due to the almost complete charge compensation of the ion beam. In this case, the energy spread of the ion beam was about ± 1%, and the energy losses of the beam did not exceed 0.5 MeV at the exit of accelerator (see Fig. 3,c).

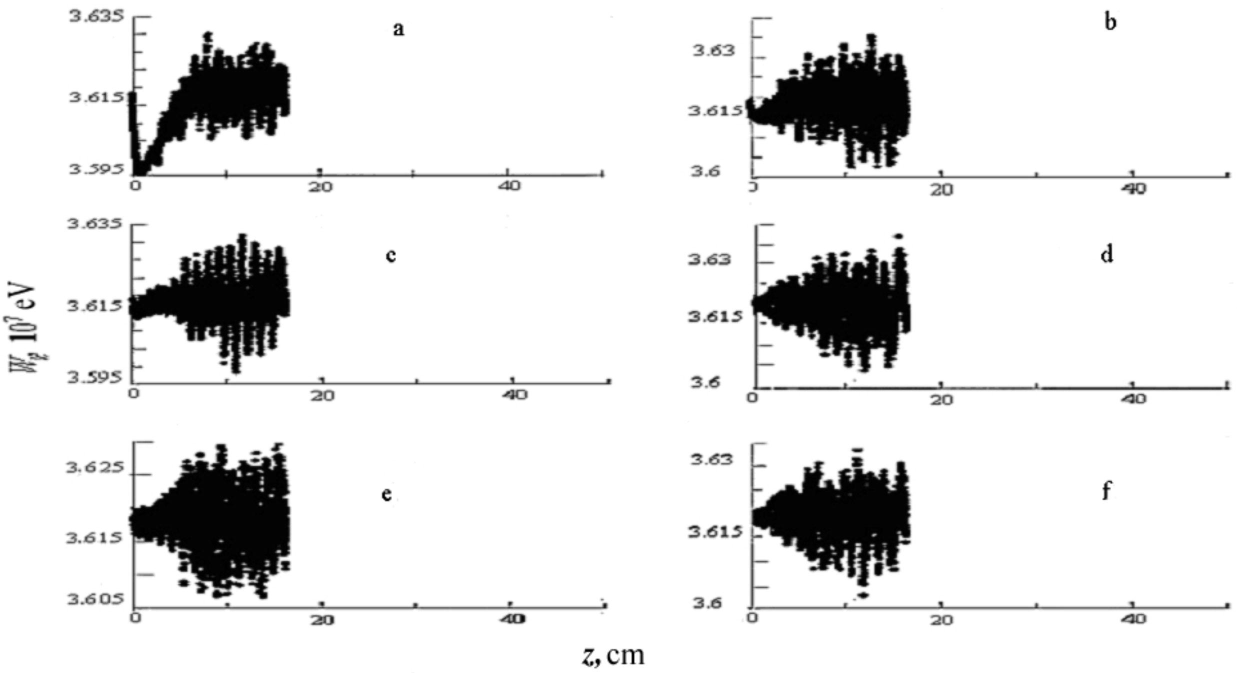

Fig. 2. The dependence of the CIB kinetic energy W_k versus the longitudinal coordinate z: (a, b) corresponds to the absence of additional electrons, and (c, d) – presence of additional electrons injection, (e, f) – the presence of a self-consistent injection of additional electrons, the left column corresponds to absence of magnetic field, the right – to the magnetic field H_0 = 0.23 T

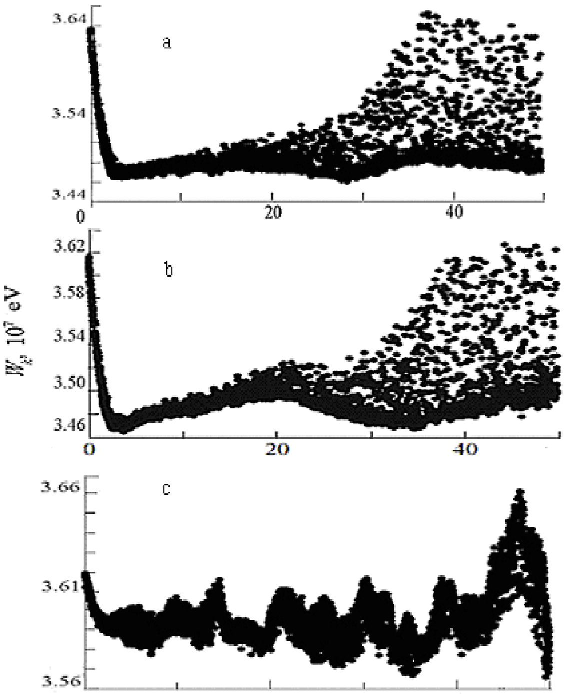

Fig. 3. The dependence of the kinetic energy of the CIB W_k versus the longitudinal coordinate z: (a) corresponds to the absence of additional electrons, and (b) – the presence of additional electron injection, and (c) – the presence of a self-consistent injection of additional electrons, (a, b, c) corresponds to the presence of external magnetic field H_0 = 0.23 T

Fig. 4 shows the (*x*,*z*)-space for the ions in the presence of self-consistent injection of additional electrons in the absence of the external magnetic field (see Fig. 4,a) and in its presence (see Fig. 4,b).

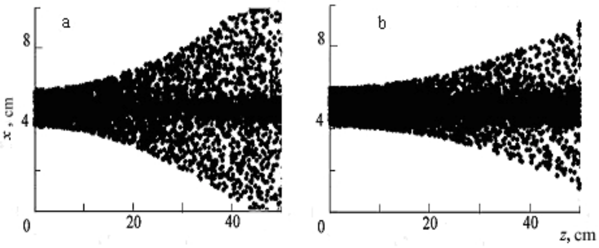

Fig. 4. The dynamics of the ion beam at its transport through the drift gap after seven electron beam transit-time of the calculated region in the space (x, z): (a) corresponds to the absence of an external magnetic field, (b) – the magnetic field H_0 = 0.23 T

It is seen, that the CIB diverges at the edges as a result of the self-consistent electromagnetic field effect. On the other hand, the redistribution of the additional thermal electrons density and the density of the electron beam leads to the focusing of the ion beam in the absence of the external magnetic field. In the presence of the external magnetic field spread of the ion beam is much smaller, and its distribution over the cross section as a result of the electromagnetic field influence is more uniform.

In Fig. 5 the ion energy distribution function is shown.

We see that even in the absence of the external magnetic field, the ion beam remains almost monoenergetic (see Fig. 5,a). The presence of the external magnetic field leads to improving of the ion energy distribution function quality (see Fig. 5,b).

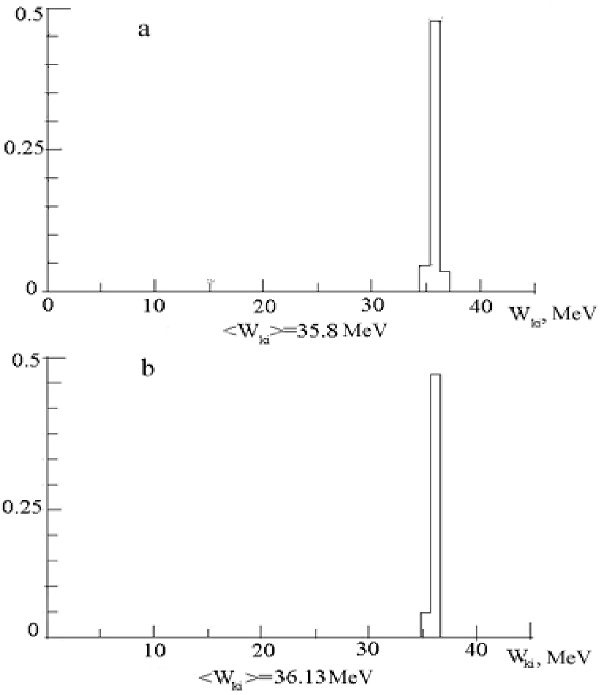

Fig. 5. Ion distribution function over energy W_{ki} at the presence of electron self-consistent injection: a) corresponds to the absence of an external magnetic field, b) – the magnetic field H_0 = 0.23 T

CONCLUSIONS

It is shown, that at the transport of ion beam with current density of about 9 MA/m^2 through drift gap high-frequency beam and filamentation instabilities develop. The considered cases are: presence of additional electron injection, the presence of an additional electron self-consistent injection, the absence of any injection. In all three studied cases as filamentation and high frequency beam instabilities take place. But the behavior of the particles depending on the injection of additional thermal electrons is somewhat different.

The self-consistent injection of additional thermal electrons in the drift gap, in the presence of the external magnetic field, leads both to CIB monochromaticity, and reduces the ion beam radius. At the same time, despite the development of instabilities compensating electron and compensated ion beams keep the current density closed to the initial one.

In all the cases, in the absence of an external magnetic field instabilities development significantly reduces the quality of the ion beam. In the presence of an external longitudinal magnetic field CIB quality remains acceptable even in the absence of additional thermal electrons, but the injection of additional electrons considerably improves the parameters of the ion beam.

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Article received 10.04.2013.

УСТОЙЧИВОСТЬ СИЛЬНОТОЧНОГО ИОННОГО ПУЧКА В ДРЕЙФОВОМ ПРОМЕЖУТКЕ ЛИНЕЙНОГО ИНДУКЦИОННОГО УСКОРИТЕЛЯ

В.И. Карась, О.В. Мануйленко, В.П. Тараканов, О.В. Федоровская

Представлены результаты численного моделирования транспортировки КИП плотностью тока 9 МА/м^2 через дрейфовый промежуток линейного индукционного ускорителя. Рассмотрена устойчивость КИП для трех методов компенсации ионного пучка по заряду в отсутствие и при наличии внешнего магнитного поля. Показано, что при наличии внешнего магнитного поля развитие неустойчивостей не приводит к существенному ухудшению качества ионного пучка независимо от способа компенсации. Показано, что наиболее эффективной докомпенсацией ионного пучка по заряду является применение самосогласованной инжекции дополнительных электронов, что приводит к сохранению параметров КИП, достаточных для его использования в тяжелоионном инерциальном синтезе.

СТІЙКІСТЬ СИЛЬНОСТРУМОВОГО ІОННОГО ПУЧКА В ДРЕЙФОВОМУ ПРОМІЖКУ ЛІНІЙНОГО ІНДУКЦІЙНОГО ПРИСКОРЮВАЧА

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

Представлені результати чисельного моделювання транспортування КІП густиною струму 9 МА/м^2 через дрейфовий проміжок лінійного індукційного прискорювача. Розглянута стійкість КІП для трьох методів компенсації іонного пучка за зарядом при відсутності та наявності зовнішнього магнітного поля. Показано, що при наявності зовнішнього магнітного поля розвиток нестійкостей не призводе до суттєвого погіршення якості іонного пучка незалежно від способу компенсації. Показано, що найбільш ефективною докомпенсацією іонного пучка за зарядом є застосування самоузгодженої інжекції додаткових електронів, що призводить до збереження параметрів КІП, достатніх для його використання у важкоіонному інерціальному синтезі.