ACCELERATION OF THE SHORT HIGH-CURRENT COMPENSATED ION BUNCHES IN THE PEAKED FENCE MAGNETIC FIELD WITH ADDITIONAL SPACE CHARGE COMPENSATION BY THERMAL ELECTRONS: 2D3V PIC SIMULATION

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The particle in cell simulation results, within the limits of the complete set of the Maxwell-Vlasov equations, of the short high-current compensated tubular ion bunches transportation and acceleration in the peaked fence magnetic field are presented. The ion bunch current, at injection in the cusp, is compensated by electrons. It is shown that additional compensation of the accelerated ion bunch space charge by thermal electrons leads to reduction of its energy dispersion and divergence on an exit from the cusp. It is shown also that overcompensation of the ion bunch space charge by thermal electrons leads not only to increase of energy spread and divergence of an ion bunch on an exit from the cusp, but also to deceleration of an ion bunch.

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INTRODUCTION

The usage of linear induction accelerators (LIA) for obtaining high-current ion beams (HCIB) with the parameters required for inertial confinement fusion is perspective, as LIA can operate at high pulse frequency, and can accelerate, with efficiency of 30 %, high-current beams of virtually any ions, and perform time compression of current pulse in the acceleration process, which eliminates the operations related to the increase of current due to compression rings. Collective focusing techniques can significantly increase the ion beam current and reduce its energy while maintaining the required energy content of the beam on the target. In such kind of LIA the ion beam space charge is compensated by electrons, and the electron current is suppressed by magnetic insulation of accelerating gaps [1,2]. The mechanism for charge and current neutralization of an HCIB by an electron beam in an axisymmetric accelerating gap was investigated in [2-4]. Transportation and acceleration of continuous compensated ion beam in a system consisting of 1…6 cusps was studied in [5,6]. It is shown that the ion energy distribution function of the HCIB at the exit of the accelerator improves with increasing energy of the accompanying electron beam. Additional injection of electron beams in the cusps increases monoenergetic of the HCIB and reduces its divergence. Transport of short, compared to the cusp length, high-current electron and ion bunches was studied in [7]. In this work the particle in cell simulation results for the short high-current compensated tubular ion bunches transportation and acceleration in the peaked fence magnetic field are presented.

Fig. 1 shows an axial section of the simulated structure, the configuration of the external magnetic field [9,10] and the place of the beams injection. The length of the cusp is z_L = 10.24 cm, its radius is r_L = 10.24 cm, [0, z_I] and [z_{II} , z_L] are the drift spaces, z_I = 4.8 cm, z_{II} = 5.44 cm, [z_I , z_{II}] is the accelerating gap. The minimal and maximal radius of the electron and ion bunches are the same: $r_{\min}$ = 1.32 cm, $r_{\max}$ = 1.48 cm. At the time of injection $n_{e0}v_{e0} = n_{i0}v_{i0}$, the electron bunch density is n_{e0} = 7.12·10^{13} cm^{-3}, the electron bunch velocity is v_{e0} = 0.95·c, the initial velocity of the ion bunch (protons) is v_{i0} = 0.285·c, c is the speed of light. The bunch length is 0.5 z_I , or $\tau_{bunch} = 0.5 \cdot z_I / v_{i0}$. The external magnetic field has a cusp configuration [10] with amplitude H_0 = 47 kGs. In some simulations (see below) in regions $[0, z_I] \times [r_{\min}, r_{\max}]$, $[z_{II}, z_L] \times [r_{\min}, r_{\max}]$, there was a generation of Maxwellian electrons with temperature T_e = 1 keV. These electrons are intended to further compensation of the space charge of the ion bunch. The generation begins at the moment when the front of the bunch crossing the left border of each drift gap, and ended when the front of the bunch crossing its right border. The generation rate is chosen so that at the time of its termination the electron density is n_e^{comp} =0.5 n_{i0} , or n_e^{comp} =1.0 n_{i0} , or n_e^{comp} =2.0 n_{i0} .

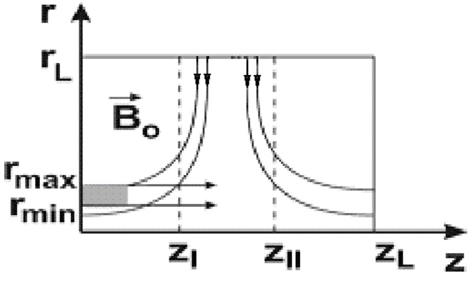

Fig. 1. Configuration of the external magnetic field and regions of electron and ion bunches injection into the computation domain

The outer boundaries of the system are perfectly conducting metal walls. Particles that fall into the boundaries are removed from the simulation. Particle in cell simulation scheme is described in detail in [5].

SIMULATION RESULTS

Fig. 2 shows the simulation results for the transport of the high – current compensated ion bunch (IB) through the cusp. Ion distribution functions (IDFs) along the transverse coordinate at the right cusp boundary are presented in Fig. 2,a,c,e,g. IDFs depending on energy (IEDFs) and transverse coordinate at the exit of the cusp are shown in Fig. 2,b,d,f,h. Fig. 2,a,b – the generation of thermal electrons is absent, Fig. 2,c,d – at the termination time for the generation of thermal electrons n_e^{comp} = 0.5 n_{i0}, Fig. 2,e,f – at the termination time for the generation of thermal electrons n_e^{comp} = 1.0 n_{i0}, and Fig. 2,g,h – at the termination time for the generation of thermal electrons n_e^{comp} = 2.0.

As can be seen from Fig. 2, IBs are well focused in the transverse direction, however, after the passage of the cusp, IEDFs are significantly different depending on the density of compensating thermal electrons. At low densities of thermal electrons ($n_e^{comp} < 1.0\, n_{i0}$) IEDFs almost monochromatic, while at higher densities of compensating thermal electrons ($n_e^{comp} > 1.0\, n_{i0}$) there is a substantial spread in the ion energy. IEDF has a maximum at $\varepsilon_m \approx 25$ MeV for n_e^{comp} = 0, $\varepsilon_m \approx 25$ MeV for n_e^{comp} = 0.5 n_{i0}, $\varepsilon_m \approx$ 18 MeV for n_e^{comp} = 1.0 n_{i0}, and $\varepsilon_m \approx$ 14 MeV for n_e^{comp} = 2.0 n_{i0}.

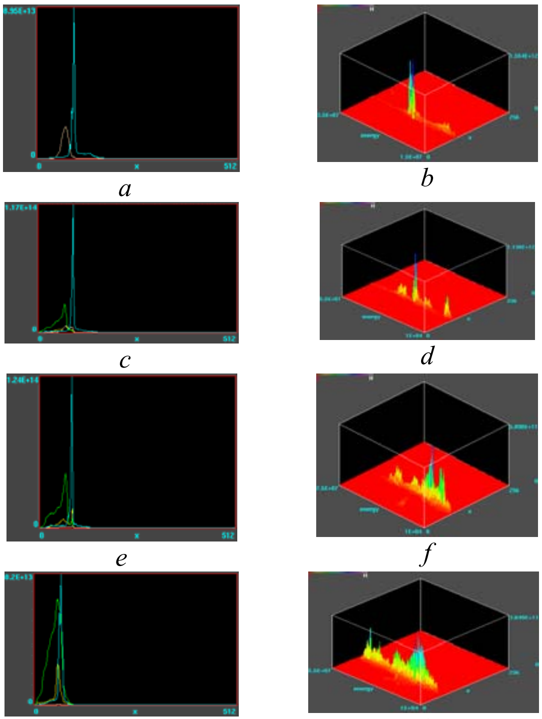
a b c d e f g h

Fig. 2. IDFs along the transverse coordinate at the right cusp boundary - a,c,e,g. IDFs vs energy and transverse coordinate at the exit of the cusp – b,d,f,h. a,b – the generation of thermal electrons is absen. c,d – at the termination time for the generation of thermal electrons n_e^{comp} = 0.5 n_{i0}. e,f – n_e^{comp} = 1.0 n_{i0}. g,h – n_e^{comp} = 2.0

The increase in the ion energy spread and the fall of $\varepsilon_{\max}$ with the growth of n_e^{comp} can be explained by the fact that the compensating thermal electrons loaded IB, taking part its its kinetic energy. This is clearly seen in the electron energy distribution function on the right edge of the cusp - compensating electrons from the left side of the cusp always have an average energy exceeding the initial one. Thus, there is an optimal density of compensating thermal electrons n_e^{comp} above which the quality of the transported IB sharply deteriorates.

Fig. 3 shows the simulation results for the acceleration of the high-current compensated IB in the cusp. Accelerating potential is 1 MB. IDFs along the transverse coordinate at the right cusp boundary are presented in Fig. 3,*a, c, e, g*. IDFs depending on energy and transverse coordinate at the exit of the cusp are shown in Fig. 3,*b, d, f, h*. Fig. 3,*a,b* - the generation of thermal electrons is absent, Fig. 3,*c,d* - at the termination time for the generation of thermal electrons n_e^{comp} = 0.5 n_{i0}, Fig. 3,*e,f* - at the termination time for the generation of thermal electrons n_e^{comp} = 1.0 n_{i0}, and Fig. 3,*g,h* - at the termination time for the generation of thermal electrons n_e^{comp} = 2.0.

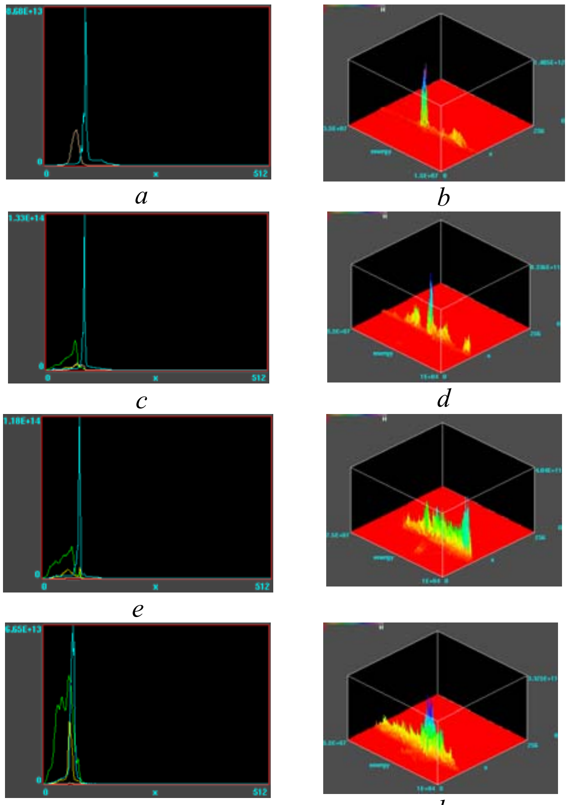
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Fig. 3. IDFs along the transverse coordinate at the right cusp boundary – a,c,e,g. IDFs vs energy and transverse coordinate at the exit of the cusp – b,d,f,h. a,b – the generation of thermal electrons is absen. c,d – at the termination time for the generation of thermal electrons n_e^{comp} = 0.5 n_{i0}. e,f – n_e^{comp} = 1.0 n_{i0}. g,h – n_e^{comp} = 2.0. Accelerating potential is 1 MB

As can be seen from Fig. 3, IBs are well focused in the transverse direction, however, as in the case of transport, after the passage of the cusp, IEDFs are significantly different depending on the density of compensating thermal electrons. At low densities of thermal electrons ($n_e^{comp} <$ $1.0\, n_{i0}$) IEDFs almost monochromatic, while at higher densities of compensating thermal electrons ($n_e^{comp} >$ $1.0\, n_{i0}$) there is a substantial spread in the ion energy. IEDF has a maximum at $\varepsilon_m \approx 26$ MeV for $n_e^{comp} = 0$, $\varepsilon_m \approx 26$ MeV for $n_e^{comp} = 0.5\, n_{i0}$, $\varepsilon_m \approx 19$ MeV for $n_e^{comp} = 1.0\, n_{i0}$, and $\varepsilon_m \approx 15$ MeV for $n_e^{comp} = 2.0\, n_{i0}$. Thus, regardless of the n_e^{comp}, there is an acceleration of the IB. The increase in the ion energy spread and the fall of $\varepsilon_{\max}$ with the growth of n_e^{comp} can be explained in the same way as in the case of transportation. Hence, there is an optimal n_e^{comp} above which the quality of the transported IB sharply deteriorates.

CONCLUSIONS

The particle in cell simulation results, within the limits of the complete set of the Maxwell-Vlasov equations, for the short high-current compensated tubular ion bunches transportation and acceleration in the peaked fence magnetic field are presented. The ion bunch current, at injection in the cusp, is compensated by electrons. It is shown that additional compensation of the accelerated ion bunch space charge by thermal electrons leads to reduction of its energy dispersion and divergence on an exit from the cusp. It is shown also that overcompensation of the ion bunch space charge by thermal electrons leads not only to increase of energy spread and divergence of an ion bunch on an exit from the cusp, but also to deceleration of an ion bunch.

REFERENCES

1. O.V. Batishchev, V.I. Golota, et al. Linear induction accelerator of charge-compensated ion beams for ICF // *Fiz. Plazmy.* 1993, v. 19, № 5, p. 611-644.
2. V.I. Karas', V.V. Mukhin, et al. About compensated ion beam acceleration in magnetoisolated systems // *Fiz. Plazmy.* 1987, v. 13, № 4, p. 494-496.
3. N.G. Belova, V.I. Karas', Yu.S. Sigov. Numerical simulation of charged particle beam dynamics in axial symmetric magnrtic field // *Fiz. Plazmy.* 1990, v. 16, № 2, p. 209-215.
4. 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.
5. O.V. Bogdan, V.I. Karas', et al. 2.5-dimensional numerical simulation of a high-current ion linear induction accelerator // *Plasma Phys. Rep.* 2008, v. 34, № 8, p. 667-677.
6. O.V. Bogdan, V.I. Karas', et al. Numerical simulation of high-current ion linear induction accelerator with additional electron beam injection *// Problems of Atomic Science and Technology. Ser. «Nuclear Physics Investigations»* (53). 2010, № 2, p. 106-110.
7. O.V. Manuilenko. Dynamics of the short high-current electron and ion bunches in the peaked fence magnetic field: 2d3v PIC simulation *// Problems of Atomic Science and Technology. Ser. «Nuclear Physics Investigations» (79).* 2012, № 3, p. 183-187.

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УСКОРЕНИЕ КОРОТКИХ СИЛЬНОТОЧНЫХ КОМПЕНСИРОВАННЫХ ИОННЫХ СГУСТКОВ В МАГНИТНОМ ПОЛЕ ОСТРОУГОЛЬНОЙ ГЕОМЕТРИИ С ДОПОЛНИТЕЛЬНОЙ КОМПЕНСАЦИЕЙ ОБЪЕМНОГО ЗАРЯДА ТЕПЛОВЫМИ ЭЛЕКТРОНАМИ: 2.5-МЕРНОЕ ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ

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Приведены результаты моделирования методом макрочастиц в рамках полной системы уравнений Власова-Максвелла, транспортировки и ускорения коротких сильноточных трубчатых ионных сгустков в магнитном поле остроугольной геометрии. Ток ионного сгустка при инжекции в касп скомпенсирован электронами. Показано, что дополнительная компенсация объемного заряда ионного сгустка тепловыми электронами приводит к уменьшению его энергетического разброса и расходимости на выходе из каспа. Показано также, что перекомпенсация объемного заряда ионного сгустка тепловыми электронами ведет не только к увеличению разброса по энергии и расходимости ионного пучка на выходе из каспа, но и к замедлению ионного сгустка.

ПРИСКОРЕННЯ КОРОТКИХ СИЛЬНОСТРУМОВИХ КОМПЕНСОВАНИХ ІОННИХ ЗГУСТКІВ У МАГНІТНОМУ ПОЛІ ГОСТРОКУТНОЇ ГЕОМЕТРІЇ З ДОДАТКОВОЮ КОМПЕНСАЦІЄЮ ОБ'ЄМНОГО ЗАРЯДУ ТЕПЛОВИМИ ЕЛЕКТРОНАМИ: 2.5-ВИМІРНЕ ЧИСЛОВЕ МОДЕЛЮВАННЯ

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Наведено результати моделювання методом макрочасток у рамках повної системи рівнянь Власова-Максвелла, транспортування та прискорення коротких сильнострумових трубчастих іонних згустків у магнітному полі гострокутної геометрії. Струм іонного згустка при інжекції у касп, скомпенсовано електронами. Показано, що додаткова компенсація об'ємного заряду іонного згустка тепловими електронами приводить до зменшення його енергетичного розкиду і розбіжності на виході з каспа. Показано також, що перекомпенсація об'ємного заряду іонного згустка тепловими електронами веде не тільки до збільшення розкиду по енергії і розбіжності іонного пучка на виході з каспа, але і до уповільнення іонного згустка.