https://doi.org/10.46813/2023-148-096

ISOLATION OF ELECTRONS BY THE MAGNETIC FIELD OF A CUSP FOR HIGH-DENSITY ION BEAM ACCELERATION

O.V. Fedorovskaya, V.I. Maslov, I.N. Onishchenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: onish@kipt.kharkov.ua

2.5D numerical simulation was carried out of the process of ions isolation from electrons of a compensated ion beam by the cusp magnetic field of the before entering the accelerating gap located in the region of zero magnetic field of the cusp, followed by the compensation of the accelerated ion beam with new electrons and transportation of the compensated ion beam to the next section of the linear induction ion accelerator. In contrast to the previously simulated compensated high-current ion beam with an energy of 250 keV (now non-existent), the equivalent plasma flow of a traditional coaxial plasma gun with real parameters: density $10^{10}…10^{12}$ cm^{-3} and velocity 10^7 cm/s was considered as an injected compensated ion beam.

PACS: 41.75.-i, 52.40.Mj, 52.65.Rr

INTRODUCTION

High-current ion beams are widely used in many applications, including materials science [1, 2] and inertial heavy ion fusion [3, 4]. Their production is based on the use of high-density plasma flows [5], the ion component of which, before entering the accelerating gap, gets rid of the electronic component by isolating the electrons with a transverse magnetic field.

For materials science purposes, electrons are isolated by a transverse magnetic field in a device called an ion diode with external magnetic insulation [6 - 8]. To transport dense plasma flows, clean them from impurities and inject them into magnetic traps, a curvilinear magnetic field in the form of a 90° segment of a toroidal solenoid is used [9, 10]. The same magnetic system is used for implanting intense ion flows, charge-compensated by magnetized electrons [1].

Of particular interest is the interaction of dense plasma flows with an acute-angled cusp-type magnetic system, consisting of opposing magnetic fields of two coils with oppositely directed currents. In such systems, the transverse component of the magnetic field depends on the geometry of the cusp and the radius of ion injection. For traps with a cusp magnetic field, so-called traps with min B, devoid of a number of hydrodynamic instabilities, the problem of determining the location of ion injection and the parameters that ensure their capture in the trap was studied in [11] in the single-particle approximation. Three radial regions are found that depend on the Larmor radius of the ion, determined by the ion velocity and the total magnetic field. Ions injected into the paraxial region pass through the cusp, into the middle region they are captured in the trap, and into the peripheral region they go into the slot plane of the trap.

For a dense plasma flow equivalent to a high-current ion beam, compensated for current and charge by an electron beam, the same problem was studied in [12] taking into account both the spatial charge of the beams and the polarization fields that arise during the spatial separation of the electron and ion components. In this case, the dynamics of the ion and electron components is determined by the ratio of the forces exerted on them by both the magnetic field and the polarization electric field. For the set of parameters [13] used in studying the possibility of accelerating a high-current ion beam in sectional linear ion induction accelerators with periodic isolation of electrons by the magnetic field of the cusp in front of the accelerating gap and its subsequent compensation by an electron beam for transportation to the next section, there are radical differences in the dynamics of the ion beam from the single-particle considerations arise starting from an ion beam density of 10^{12} cm^{-3}. In the specified set, however, an as yet unrealized ion beam, compensated for current and charge (i.e., plasma flow), with an energy of 250 keV, was selected as the initial injection.

In this work, a numerical simulation of the injection of a dense plasma flow with a density of more than 10^{12} cm^{-3} and a speed of about 10^7 cm/s, obtained on existing plasma accelerators [5], into the magnetic field of the cusp is carried out. The positions of electrons and ions in space obtained over time during the injection pulse make it possible to judge the isolation of electrons by the magnetic field of the cusp and the change in the parameters of the ion beam that passed the cusp into the accelerated gap, which are of great importance in the problem of inertial thermonuclear fusion [13]. In addition, the details of the process of electron isolation and the dynamics of passing cusp ions in space, obtained in the problem posed, are also of interest in the other studies listed above.

1. PROBLEM STATEMENT

The studies were carried out using 2.5-dimensional numerical modeling in *rz*-geometry using the KARAT code [14]. The model under consideration consists of an accelerating and drift gap (Fig. 1). A magnetically insulated gap (cusp) is created by two coils with opposing currents. The drift gap is a region of uniform magnetic field (B_0 = 0.05 T) created by the solenoid. In a chamber with length L = 47 cm, radius R = 7 cm, a tubular plasma flow of conventional coaxial plasma gun is injected on the left with a velocity of 10^7 cm/s and a density of 10^{12} cm^{-3}, internal and external radii r_{min} = 0.7 cm, r_{max} = 1.4 cm.

It represents an equivalent beam of ions, compensated by an electron beam with equal speeds and densities. To ensure the possibility of separating electron and ion beams in the cusp, tubular beams are considered to provide interaction of particles with nonzero radial magnetic field of cusp. An electric field with an intensity of 125 keV/cm at a length of 1 cm, located in the center of the cusp, accelerates ions without electrons isolated by the cusp. The radii of the beams satisfy the condition for ions to pass through the cusp, and the beam density and magnetic field are chosen so that the electrons are magnetized and the ions freely pass through the magnetically insulated gap [11].

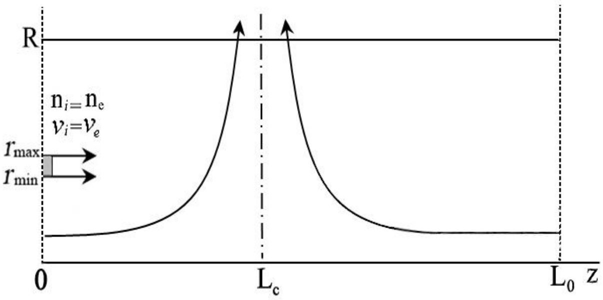

Fig. 1. Geometry of the magnetic system and the injection region of Ar^+ and electron beams

2. DISTRIBUTION OF AN ELECTRON BEAM ON THE (*r,z*) PLANE IN THE MAGNETIC FIELD OF CUSP

To verify electron magnetization, facilitating their isolation from the ion beam, the dynamics of a single electron beam with a density of 10^6 cm^{-3} in the cusp magnetic field was analyzed. In the case of axial symmetry, the distribution of particles in the (*r,z*) plane describes their distribution in the configuration space (r,φ,z). Fig. 2,a,b,c depict the distribution of the electron beam on the (*r,z*) plane at three moments in time after the start of injection.

It can be seen that the injected electrons follow on the magnetic field lines towards the periphery of the cusp. Staying between the magnetic surfaces where the beam is confined at the entrance, and they do not cross the plane of zero magnetic field. The distribution of the electron beam in the (v_z,*z*) phase space (Fig. 2,d,e,f) reveals the presence of reflected electrons. The two-stream behavior of electrons indicates the emergence of a virtual cathode analogue within the given beam and chamber parameters and geometry (see Fig. 2, f). However, this does not hinder electron isolation; instead, it leads to the accumulation of additional volume charge at the entrance, altering the polarization field.

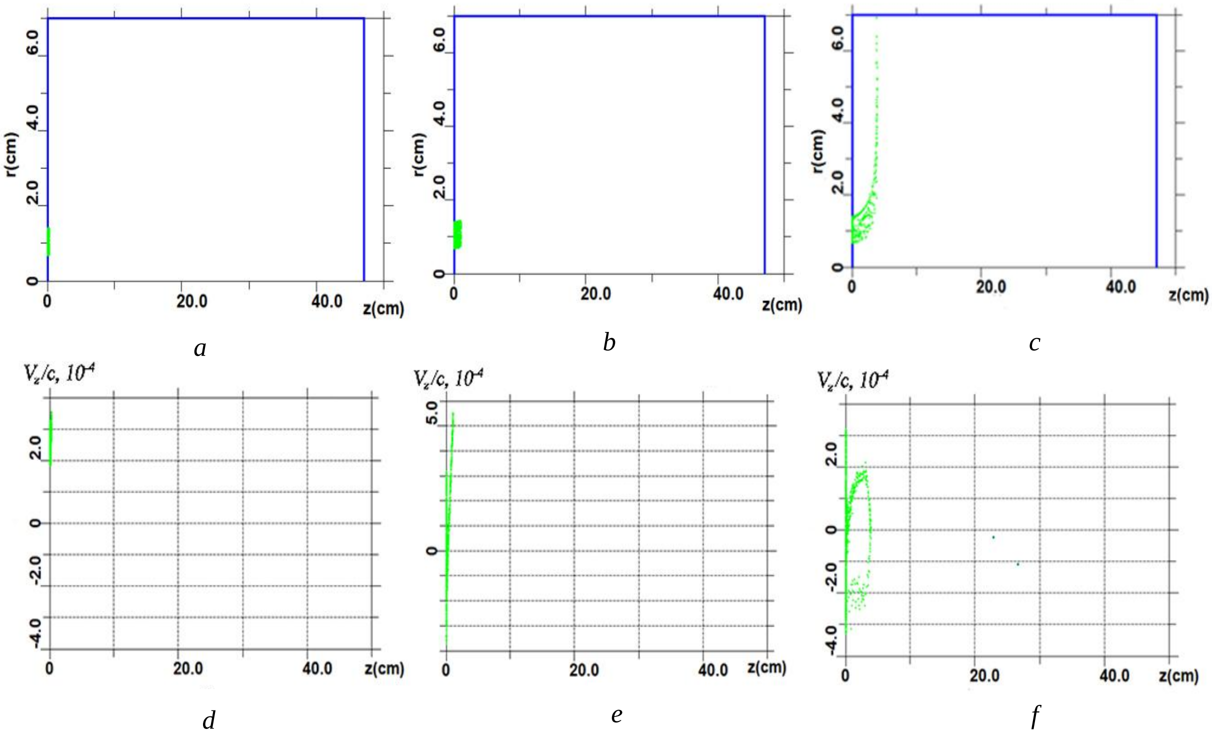

Fig. 2. The distribution of electrons on the (r,z) plane (a, b, c). The longitudinal velocity of electrons vs the longitudinal coordinate z at different moments in time. (b, e, f). 0.03 μs (a, d); 0.09 μs (b, e); 1 μs (c, f). The electron density 10^6 cm^{-3}

3. ISOLATION, ACCELERATION AND CONFIGURATION SPACE OF ARGON IONS IN A CUSP

The dynamics of the distribution of Ar+ ions on the (*r,z*) plane at a beam density of 10^8 cm^{-3} is shown in Fig. 3,a,b,c. A beam of argon ions passes through half of the cusp, acquires energy in the accelerating gap and slightly expands along the angle in the field of its own space charge in the absence of compensation by electrons (see Fig. 3,a,b,c). In the case of electron compensation, i.e. at injecting ion and electron beams (Fig. 3,d,e,f), the angular spread of the ion beam is reduced due to its compensation in the area before the electron beam is isolated.

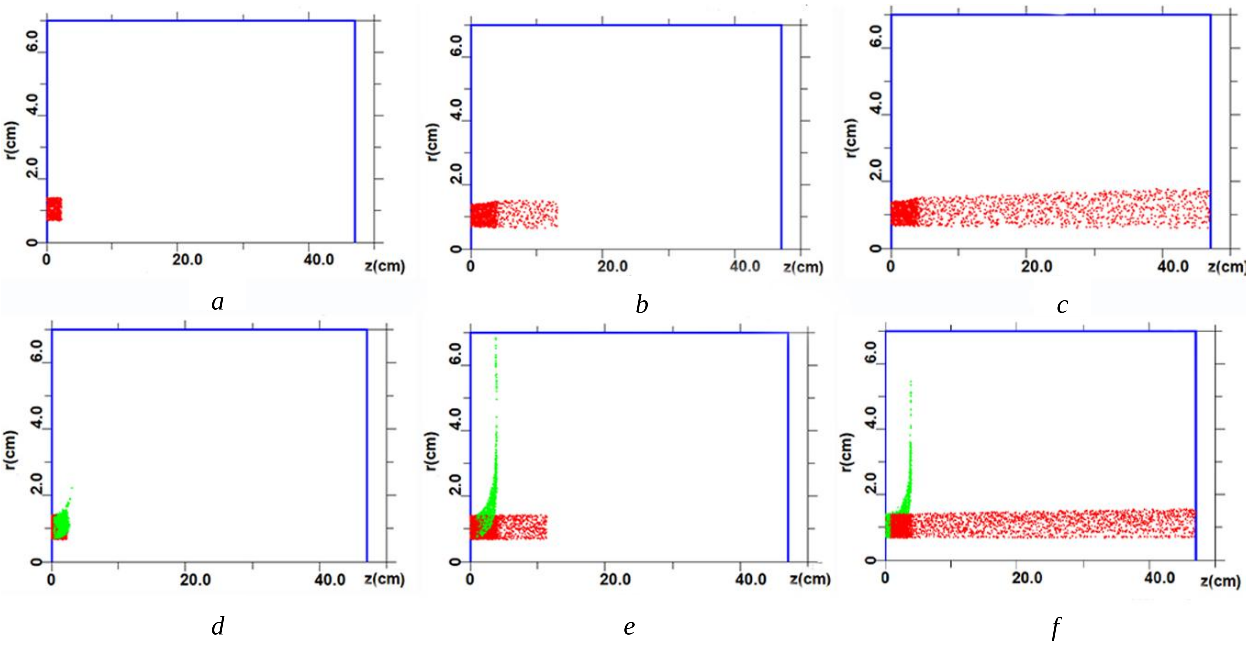

Fig. 3. Beam distribution of Ar^+ ions on surface (r,z) (a, b, c), beam distribution of Ar^+ ions (red) and a compensating electron beam (green) on the plane (r,z) (d, e, f) at different times. 0.25 μs (a, d); 0.5 μs (b, e); 1 μs (c, f). Density of ions and electrons equals 10^8 cm^{-3}

Distribution of Ar^+ ions is presented in Fig. 4 for value of beam density 10^9 cm^{-3} at different times without injection of compensating electron beam (see Fig. 4,a,b,c) and with joint injection of ion and electron beams (see Fig. 4,d,e,f). One can see (see Fig. 4,a,b,c) that the ion beam without compensation diverges significantly more in the transverse direction compared to the density 10^8 cm^{-3} (see Fig. 3,a,b,c). The transverse size of a tubular beam of argon ions, which makes an azimuthal drift in crossed electric and magnetic fields near the system axis, is determined by the radius of the ion motion cycloid. This radius grows at increasing space charge field of a denser ion beam. Because the Larmor radius of the argon ion for the selected parameters is greater than the chamber radius; it makes a slight rotation during the passage of the chamber and moves away from the axis in the radial direction under the effect of the space charge field in almost the same way as without a magnetic field.

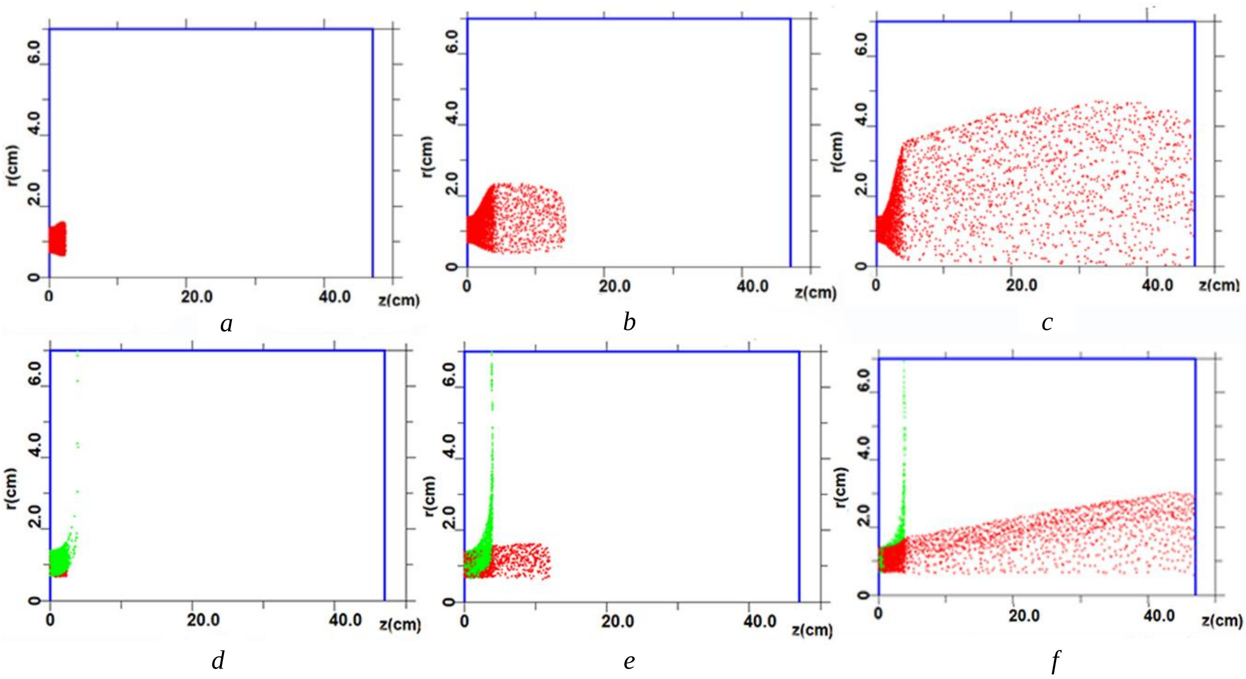

Fig. 4. Beam distribution of Ar^+ ions on surface (r,z) (a, b, c), beam distribution of Ar^+ ions (red) and a compensating electron beam (green) on the plane (r,z) (d, e, f) at different times. 0.25 μs (a, d); 0.5 μs (b, e); 1 μs (c, f). Plasma density equals 10^9 cm^{-3}

At injection of ion and electron beams (see Fig. 4,d,e,f), the space charge fields of both beams form a polarization field of the beams, separated by the magnetic field of the cusp – the electron beam goes along the magnetic field lines to the periphery, and the ion beam passes the cusp along the axis. The crossed polarization field and the cusp magnetic field lead to azimuthal drift of the beams, which does not interfere with the isolation of the electron beam and the longitudinal movement of the ion beam into the accelerating gap. However, the above-mentioned reflection of electrons from the virtual cathode already at densities above 10^6 cm^{-3} and their return along magnetic field lines and accumulation in the injection region lead to a large negative space charge. As a result, the ion flow to the accelerating gap significantly decreases and its radius increases.

This is more clearly observed for high densities. In Fig. 5 the dynamics of the ion beam shows in the presence of a compensating electron beam, when their density is equal to 10^{10} cm^{-3}. In this case, the polarization field increases so much that both beams hold each other near the injection plane and only a small part (smaller for higher density) of the electron beam goes radially along the magnetic field lines to the periphery and the ion beam along the *z* axis to the accelerating gap. In this case, the accumulated charge of electrons significantly shifts the ion beam along the radius. The accelerated part of the displaced ion beam in the region of a uniform magnetic field expands due to the space charge field.

A typical dependence of the achieved kinetic energy of an ion beam on the longitudinal coordinate *z* is illustrated in Fig. 6 for a beam density of 10^8 cm^{-3}. It corresponds to an electric field of 125 kV/cm at an accelerating gap length of 1 cm.

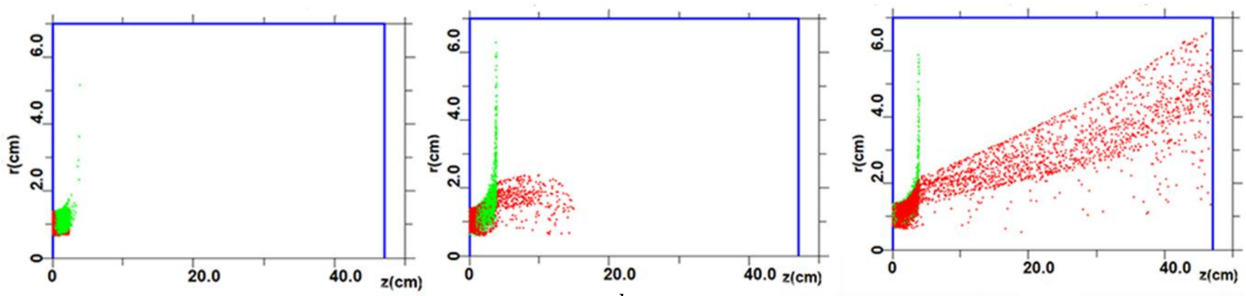

Fig. 5. Beam distribution of Ar^+ ions (red) and a compensating electron beam (green) on the r,z plane (a, b, c) at different times. 0.25 μs (a); 0.5 μs (b); 1 μs (c). Density of ions and electrons equals 10^{10} cm^{-3}

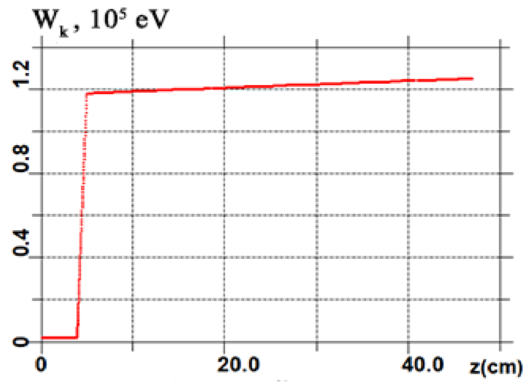

Fig. 6. Dependence of beam kinetic energy of Ar^+ ions on longitudinal coordinate at time 1 μs

CONCLUSIONS

2.5D numerical simulation of electron isolation in a dense plasma flow of existing plasma guns, as an equivalent of a high-current ion beam, compensated for current and charge by an electron beam, to accelerate the ion component using the cusp magnetic field showed that such a scheme for accelerating a high-current ion beam is more complex than currently being interpreted.

For low beam densities (under taken parameters $n_b<10^8$ cm^{-3}) the electron beam follows the cusp magnetic field lines to the periphery and thus becomes isolated from the ion beam. Meanwhile, the Ar+ ion beam passes through cusp and gains energy in the accelerating gap.

For higher densities, this scheme is modified due to the appearance of the electric field of spatially separated ion and electron beams (so-called polarization field, composed of the space charge fields of the beams). At that the electron beam following the magnetic field lines to the periphery can be reflected and return along the same magnetic field lines to the injection region, leading to the accumulation of a space charge and an increase in the polarization field. In turn, the ion beam, under the influence of the polarization field, is being held in the injection region, leading to a reduce in the ion beam current arriving to the accelerating gap and to an increase in its transverse dimensions. The negative effect of reducing the beam current (electron beam to the periphery and ion beam along the axis) increases with increasing beam density.

The application of the cusp magnetic field for the acceleration of high-current ion beams used in materials science and technological applications can be enhanced by minimizing the distance from the injection plane to the accelerating gap, thus reducing the divergence of uncompensated ion beams. However, utilizing this method in a multi-sectional induction accelerator for inertial fusion appears problematic due to the accumulation of existing ion beam expansion and the reduction of its current on each section.

REFERENCES

1. Harry Bernas (Ed.). Material Science with Ion Beams // *Topics in Applied Physics*. Springer, 2010, v. 116, p. 376.
2. I.I. Aksenov, V.A. Belous, et al. Transportation of plasma flows in a curved plasma-optical systems // *Vacuum arc, plasma sources, coatings deposition,*

surface modification. Kiev: "Naukova Dumka", 2012, Chapter 7, p. 178-190 p.

3. G.S. Kerslick, I.S. Roth, Cz. Golkowski, J.D. Ivers, and J.A. Nation. Confinement of a high current proton beam in a linear induction accelerator // *PAC.* 1987, p. 928-930.
4. V.I. Karas, E.A. Kornilov, Ya.B. Fainberg. Linear induction accelerator of charge-compensated ion beams for inertial thermonuclear fusion // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration".* 1998, № 1, p. 101-107.
5. A.I. Morozov, V.I. Tereshin, I.E. Garkusha, et al. QSPA Kh-50 full-scale high-power quasistationary plasma accelerator // *Plasma devices and operations*. 1992, v. 2, № 2, p. 155-65.
6. G.E. Remnev, I.F. Isakov, M.S. Opekounov, et al. High intensity pulsed ion beam sources and their industrial application // *Surf. & Coat. Technologies*. 1999, v. 114, p. 206-212.
7. A.V. Petrov, A.I. Ryabchikov, I.B. Stepanov, et al. High current and high intensity pulsed ion-beam sources for combined treatment of materials // *Rev. Sci. Instrument*. 2000, v. 71, p. 783-785.
8. Hiroaki Ito, Yasushi Ochiai, and Katsumi Masugata. Development of High-current Pulsed Heavy-ion-beam Technology for Applications to Materials Processing // *Journal of the Korean Physical Society*. 2011, v. 59, № 6, p. 3652-3656.
9. G. Schmidt. Plasma motion in a curved magnetic field // *The Phys. of Fluids*. 1962, v. 5, № 8, p. 994-1002.
10. V.S. Voitsenya, I.N. Onishchenko N.A. Hizhnyak, et al. Motion of a plasmoid in a curvilinear magnetic field // *Sov. Phys. Tech. Phys*. 1967, v. 12, p. 185-192.
11. K.D. Sinelnikov, N.A. Hizhnyak, N.S. Repalov, et al. Investigation of the motion of particles in magnetic traps of acute-angled geometry // *Plasma Physics and Problem of Controlled Thermonuclear Fusion.* Kiev: "Naukova Dumka", 1965, v. 4, p. 388-402.
12. I.N. Onishchenko, O.V. Fedorovskaya. Simulation of the compensation of a high-current ion beam by an electron beam in a cusp magnetic system // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration".* 2021, № 4, p. 122-127.
13. V.I. Karas', E.A. Kornilov, O.V. Manuilenko, O.V. Fedorovskaya. Density optimization of the high-current ion beam for linear induction linac // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2012, № 3, p. 126-130.
14. V.P. Tarakanov. *User's Manual for Code KARAT.* Springfield VA: Berkley Research Associates Inc, 1992, p. 137.

Article received 20.10.2023

ІЗОЛЯЦІЯ ЕЛЕКТРОНІВ МАГНІТНИМ ПОЛЕМ КАСПА ДЛЯ ПРИСКОРЕННЯ ІОННОГО ПУЧКА ВЕЛИКОЇ ГУСТИНИ

О.В. Федорівська, В.І. Маслов, І.М. Оніщенко

Проведено 2.5D чисельне моделювання процесу ізоляції іонів від електронів компенсованого іонного пучка магнітним полем каспа до входу в прискорювальний проміжок, розташований в області нульового магнітного поля каспа, з наступною компенсацією прискореного іонного пучка новими електронами та транспортування компенсованого іонного пучка до наступної секції лінійного індукційного прискорювача іонів. На відміну від раніше змодельованого компенсованого сильнострумового пучка іонів з енергією 250 кеВ (такого зараз не існує), розглянутий як інжектований компенсований пучок іонів еквівалентний потік плазми традиційної коаксіальної плазмової гармати з реальними параметрами: щільність $10^{10}…10^{12}$ см$^{-3}$ і швидкість 10^7 см/с.