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REDUCTION OF POLARIZATION FIELD INFLUENCE ON THE COMPENSATED ION BEAM DYNAMICS IN THE INDUCTION ION ACCELERATOR BY USING A COLLECTOR OF ELECTRONS ISOLATED BY THE CUSP MAGNETIC FIELD

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The possibility to decrease the polarization field arising between accelerated ions and compensating electrons in a plasma flow injected into a magnetic cusp with an accelerating gap is shown by a 2.5D numerical simulation. Such effect is caused by implementation a collector of electrons deflected by the cusp's magnetic field. An increase in the threshold plasma flow density by using a collector that removes electrons from the process providing polarization field decrease is demonstrated. Thus, a collector is ensuring injection of the resulting high-current ion beam into the accelerating gap without deflection.

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INTRODUCTION

In the concept of heavy ion inertial thermonuclear fusion, it has been proposed [1, 2] to use a high-current ion beam accelerated to the required energy in a linear induction accelerator (LIA). To prevent radial repulsion of the ion beam by the space charge field during transportation before and after the accelerating gap, it was supposed to be compensated by an electron beam. The compensated ion beam can be considered as a neutral plasma flow. Before it enters the ion accelerating gap, electrons should be removed from the plasma flow, i.e., magnetic isolation of electrons should be realized. This is supposed to be done by a magnetic field of the cusp geometry (the field of two solenoids with counter-currents). To transport ion beam to the next LIA section it should be compensated again.

Similar magnetic isolation of plasma electrons was applied but with a strictly transverse magnetic field in so called magnetically insulated ion diode to produce high-current ion beams for materials science applications [3, 4].

In our previous work [5] it was demonstrated that, for the selected parameters of the experimental setup, electron isolation by the cusp magnetic field before the accelerating gap is achieved only for plasma density below 10^8cm^{-3}. At higher densities, ions are deflected by the polarization field toward the periphery. With increased plasma densities, a virtual cathode forms, leading to ion concentration near the injection plane.

The aim of this study is the investigation of the possibility to increase the threshold plasma density and, consequently, the ion beam density by placing a metallic plate as a collector of electrons isolated by the cusp magnetic field. Removing deflected electrons from the process allows reducing the influence of the polarization field on the ion beam dynamics, so that ion beam with higher density can rectilinearly propagate to the accelerating gap. The propagation distance of the uncompensated ion beam to the accelerating gap must be minimal to avoid angular divergence of the beam under the action of the space charge field.

1. STATEMENT OF THE PROBLEM

The research was carried out using 2.5-dimensional numerical simulation in rz-geometry using the KARAT code. In this work, the number of cells during numerical modeling execution was: along r – I_{max} = 200, along z – J_{max} = 400, time step $3.3 \cdot 10^{-13}$ s. The duration of numerical calculations corresponds to the stationary mode (1 μs).

The system under consideration is a magnetically insulating gap, the magnetic field configuration of which is created by two coils with counter currents (so-called cusp). The maximum value of the magnetic field in the cusp is B_0=0.05 T (Fig. 1).

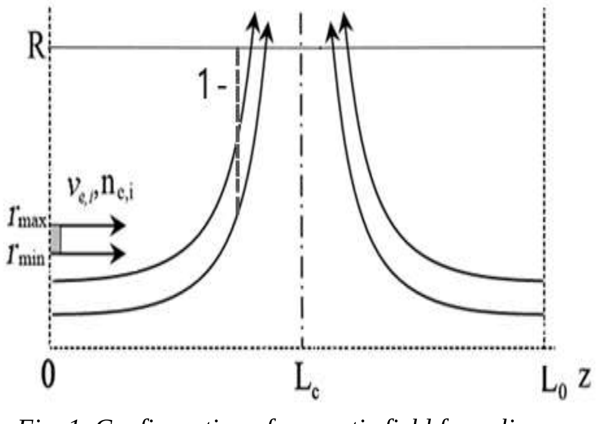

Fig. 1. Configuration of magnetic field force lines. The place of injection of tubular beams of electrons and Ar+ ions of the same densities and velocities. 1 – metallic plate

A tubular compensated beam of Ar+ ions with inner and outer radii r_{min}=1.3 cm and r_{max}=1.5 cm, respectively, is injected into the chamber with radius R=5 cm and length L_0=13 cm from the left.

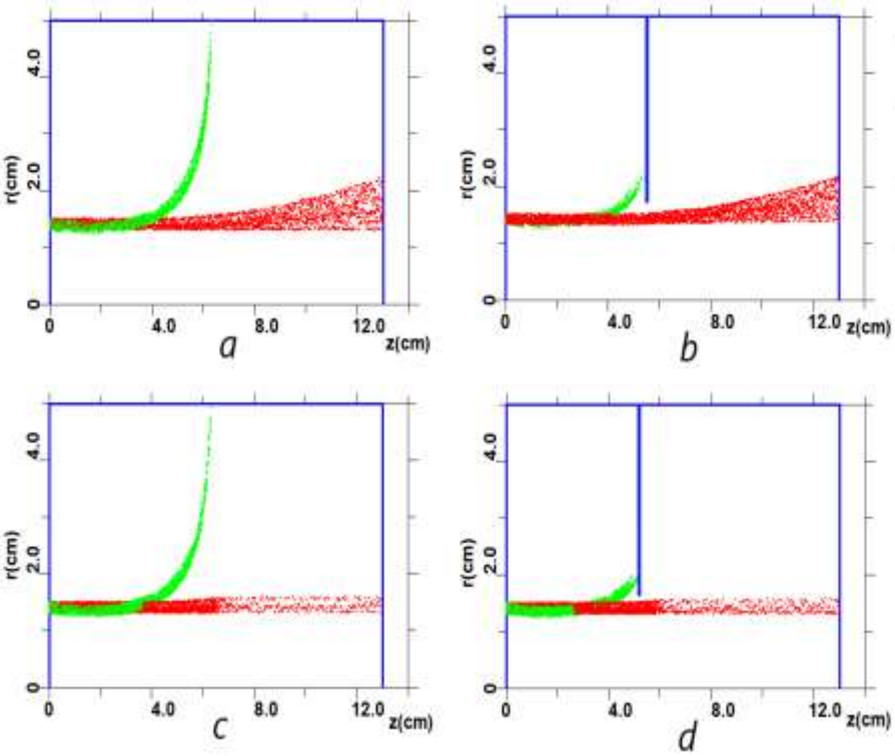

Fig. 2. Distribution of the Ar+ ion beam (red) and the compensating electron beam (green) on the rz-plane: without plate (a, c), with plate (blue) (b, d).
a, b – E_z=0; c, d – E_z=250 kV/cm. The density of the ion and electron beams is 10^9 cm^{-3}

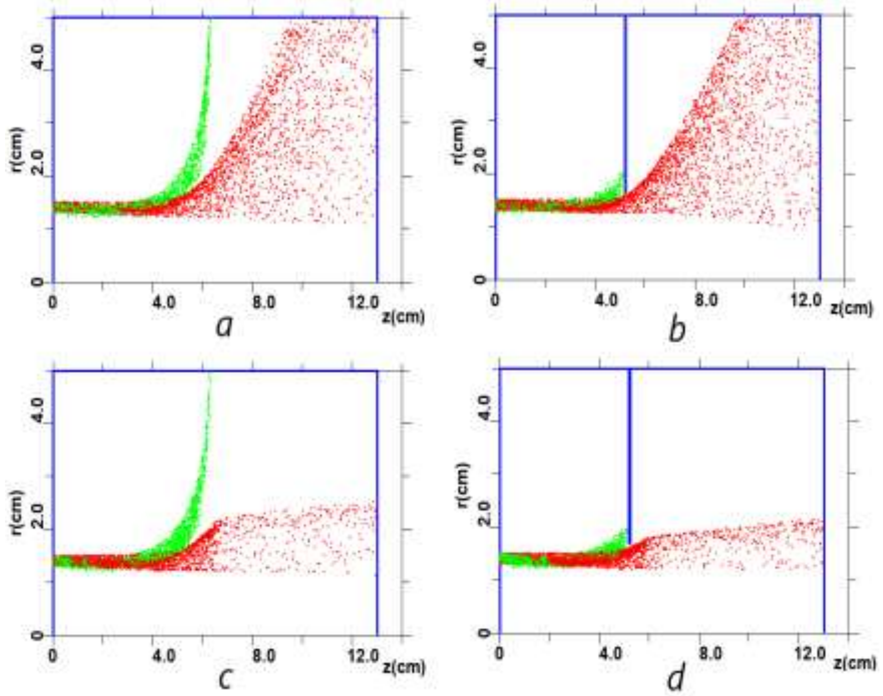

Fig. 3. Distribution of the Ar+ ion beam (red) and the compensating electron beam (green) on the rz-plane: without plate (a, c), with plate (blue) (b, d).
a, b – E_z=0; c, d – E_z=250 kV/cm. The density of the ion and electron beams is 10^{10} cm^{-3}

Radii of the beams have been chosen so, that r_{min}, r_{max}< 0.71ρ_L, where $\rho_L = M v_0/eB_0$ to ensure the passage of ions through the cusp magnetic field in the single-particle approximation [6]. The value of the initial density of the beams varied from 10^9 to 10^{10} cm^{-3}, the initial speed of $2{\cdot}10^7$ cm/s. Both the case of the absence and the presence of a metallic plate in the cusp have been considered. A metal plate with a hole (diameter of 3.3 cm) for passing the ion beam through the cusp is placed in the first half of the chamber at a distance of 2 cm from its center (see Fig. 1). After the isolation of electrons, the ion beam passes into the accelerating gap, in which an electric field E_z=250 kV/cm is applied.

The beams' density and the value of a magnetic field are chosen so that the electrons are magnetized, i.e. $\omega_B > \omega_p$, where ω_B and ω_p are cyclotron and plasma frequencies, correspondingly.

2. INFLUENCE OF THE POLARIZATION FIELD ON THE ELECTRON AND ION BEAM BEHEAVOUR

Earlier [5], it was shown that with the given system parameters and beams density 10^8 cm^{-3}, the electron beam (the electron component of the plasma flow) follows the magnetic field lines of the cusp towards the periphery, i.e., magnetic isolation of the electron beam is being realized, and the ion beam is injected into the accelerating gap without deflection. Magnetic isolation of the electron beam also occurs at a density of 10^9 cm^{-3}; however, under the influence of a significantly increased polarization field, the ion beam deviates from rectilinear motion towards the accelerating gap and expands in cross-sectional size [5]. At a beams density of 10^{10} cm^{-3}, the ion beam is entirely carried by the electron beam to the chamber walls.

In this article, to reduce the polarization field and its influence on the ion beam dynamics, it is proposed to place a metallic plate across the chamber as a collector of electrons following the cusp magnetic field lines, aiming to prevent their contribution to the polarization field. The position of the plate is chosen so that the electrons, isolated from the ions and following the magnetic field force lines, deposit on the plate before reaching the chamber walls. This setup reduces the polarization field in the subsequent part of the ion beam path toward the accelerating gap and decreases its radial deflection.

Results of numerical simulation of electron and ion beam dynamics before and after passing accelerating gap with or without electric field applied are presented in Fig. 2, for the metallic plate presence or absence and beams' density of 10^9 cm^{-3}.

From the Fig. 2,a follows that without both the metallic plate and the accelerating electric field the electron beam becomes isolated by cusp magnetic field and the uncompensated ion beam as a whole passes through the entire cusp system. The significant angular divergence is caused by the polarization field and the self field of space charge.

In the presence of the metallic plate (see Fig. 2,b), the polarization field exists only before the metallic plate, and its entirely influence on the dynamics of the uncompensated ion beam is negligible. The slightly smaller angular divergence of the un-compensated ion beam in comparison to previous case is explained by its shorter time of stay in the polarization field (duration of motion up the metallic plate).

At the presence of applied accelerating field of E_z=250 kV/cm (see Fig. 2,c,d), the accelerated ion beam density decreases that leads to significantly smaller its angular divergence after passing accelerated gap. The difference in the ion beam dynamics with and without the metallic plate becomes even less compared to the case with E_z=0.

In both cases if metallic plate is located after electrons isolation in the place where ion beam cross-section is almost the same as injected one the resulting ion dynamics is almost the same for the metallic plane presence or not. Consequently, for compensated ion beam densities less than n_b=10^9 cm^{-3}, the polarization field arising at the magnetic isolation of electrons is sufficiently weak to influence on the ion beam dynamics, both with and without the plate.

At beams' density of 10^{10} cm^{-3}, the influence of the polarization field on the ion beam becomes more significant. In the absence of the plate and the accelerating field, the electron beam and the main part of the ion beam move to the chamber walls (Fig. 3,a). The ion beam transverse dimensions become comparable to the dimensions of the chamber at a distance of 9 cm.

In the presence of the metallic plate that removes electrons from the plasma flow immediately after their isolation by the cusp magnetic field, the uncompensated ion beam with an increased density of 10^{10} cm^{-3} also diverges significantly, but this is due only to the self field of space charge. (see Fig. 3,b). Due to the absence of the polarization field in this case, the angular divergence is still smaller compared to the case without a plate.

Reducing the strong divergence of the high-density ion beam in its self field of space charge is possible by shortening the distance of its movement to the accelerating gap. The accelerated ion beam has a lower density, decreases its self field of space charge and, consequently, the angular divergence (see Fig. 3,c,d).

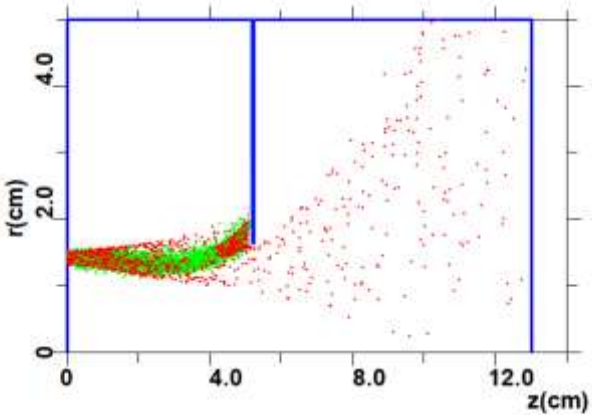

Fig. 4. Distribution of the Ar+ ion beam (red) and the compensating electron beam (green) on the rz-plane: the chamber with plane. E_z=0. The density of the ion and electron beams is 10^{11} cm^{-3}

The case of a beam density of 10^{10} cm^{-3} without the plate, when magnetically isolated electrons are not removed by the plate, leading to the formation of a polarization field that deflects the ion beam until it reaches the accelerating gap with electric field of E_z=250 kV/cm is shown in Fig. 3,c. After acceleration, the angular divergence of the ion beam significantly decreases compared to the case of E_z=0 (see Fig. 3,a), in accordance with the above statement.

If the plate and the accelerating gap with electric field of E_z=250 kV/cm are positioned at the place where the electrons have been isolated, the divergence of the uncompensated ion beam is minimized (see Fig. 3,d).

Further increasing the beams density with the taken parameters prevents effective isolation of the electron beam and transportation of the uncompensated ion beam to the accelerating gap. The distribution of beams with a density of 10^{11} cm^{-3} in the *rz*-plane is presented in Fig. 4. It is seen that the electron and ion beams, remaining unseparated, follow the magnetic field lines of the cusp and deposit on the plate. Only a small fraction of ions, acquiring transverse velocity at the initial stage, spreads throughout the chamber.

CONCLUSIONS

The transport and acceleration of an ion beam, compensated by an electron beam, were examined in a magnetic cusp and accelerating field to investigate the potential of using a metallic plate to reduce the influence of the polarization field on the dynamics of the ion beam arising from the magnetic isolation of electrons.

It was shown that the presence of a plate, where electrons deposit after magnetic isolation, reduces the impact of the polarization field on the ion beam.

For the given beams' and fields' parameters, the presence of the plate in the cusp sets a density threshold of 10^{10} cm^{-3}, above which magnetic isolation of the electron beam by the cusp field and the injection of an uncompensated ion beam into the accelerating gap are not realized.

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ЗМЕНШЕННЯ ВПЛИВУ ПОЛЯРИЗАЦІЙНОГО ПОЛЯ НА ДИНАМІКУ КОМПЕНСОВАНОГО ІОННОГО ПУЧКА В ІНДУКЦІЙНОМУ ПРИСКОРЮВАЧІ ІОНІВ ШЛЯХОМ ВИКОРИСТАННЯ КОЛЕКТОРА ЕЛЕКТРОНІВ, ІЗОЛЬОВАНИХ МАГНІТНИМ ПОЛЕМ КАСПУ

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2.5D числовим моделюванням показана можливість ослаблення поляризаційного поля, яке виникає між прискореними іонами і компенсуючими електронами у плазмовому потоці, що інжектується в магнітний касп з прискорювальним зазором. Такий ефект обумовлений введенням колектора електронів, що відхиляються магнітним полем каспу. Продемонстровано збільшення порога густини плазмового потоку з використанням колектора, який видаляє електрони з процесу та ослаблює поляризаційне поле. Отже, колектор забезпечує інжекцію без відхилення утворюваного сильнострумового іонного пучка в прискорювальний зазор.