https://doi.org/10.46813/2023-145-116

ACCELERATION OF COMPENSATED HIGH-CURRENT ION BEAM WITH CUSP MAGNETIC ELECTRON INSULATION IN THE ACCELERATING GAP AND SUBSEQUENT COMPENSATION WITH AN ELECTRON BEAM

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2.5D simulation of the process of the magnetic isolation of electrons and the acceleration of ions when injecting a high-current ion beam, compensated by an electron beam, into a magnetic cusp with an accelerating gap, followed by its re-compensation by another electron beam and transportation along the drift region with a longitudinal magnetic field, was carried out. The dependence of the characteristics of the accelerated and compensated ion beam at the drift region exit upon the set of initial parameters of the ion and electron beams and the values of the magnetic and accelerating electric fields was considered.

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

INTRODUCTION

High-current ion beam accelerators are widely used for surface modification in radiation materials science [1] and are being studied for their potential application in heavy ion beam inertial confinement fusion [2]. Therefore, obtaining such ion beams is a relevant scientific and technical challenge.

In this work, the dynamics of a high-current ion beam compensated by electron beams in a system consisting of an accelerating gap with a cusp magnetic isolation of electrons and drift gap with a homogeneous magnetic field is investigated by the numerical simulation using code "KARAT" [3]. In particular the case is considered when the non-compensated ion beam of the moderate current is injected into the cusp.

1. STATEMENT OF THE PROBLEM

The research was carried out using a 3-dimensional code [3] in rz-geometry (Fig. 1). In the model under consideration, the calculation region consists of an accelerating gap located in the cusp, and a drift region. The magnetic field is created by two coils with opposing currents (so called cusp) and a solenoid (region of homogeneous magnetic field B_0 = 1.1 T – drift region), followed by another cusp for the case of a multi-section induction accelerator. The length of the system is z_L = 50 cm in one case, and z_L = 45 cm in another, with a radius of r_L = 7 cm. On the left side, tubular ion beam (energy W_i = 240 keV) and electron (energy W_e= 130 eV) beams of the same velocity (v_i=v_e) and density (n_i = n_e=10^{12} cm^{-3}) are injected, with inner and outer radii of r_{min} = 0.7 cm, r_{max} = 1.4 cm [4]. The following options were considered: 1) ion beam compensation is performed by two electron beams; 2) there is only one compensating electron beam in the system, injected radially from the periphery into the second half of the cusp. The parameters of the electron beam injected into the second half of the cusp and the topography of the cusp magnetic field are chosen so that when the radially injected electron beam meets the ion beam, they have similar densities and transverse sizes. The accelerating electric field E_z is present in the first half of the cusp before its midpoint in the first case, and at the beginning of the system in the second case.

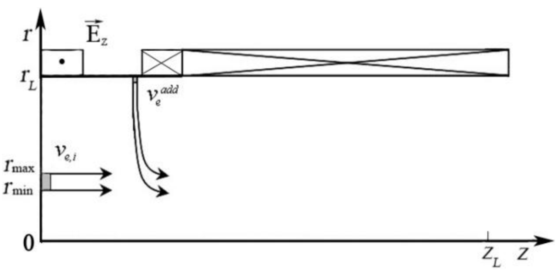

Fig. 1. Geometry of the magnetic system and the injection areas of the ion and two electron beams

2. DYNAMICS OF ION BEAM IN THE PRESENCE OF TWO COMPENSATING BEAMS

In this section the results of simulation for the first case with two compensating electron beams are presented. Fig. 2,a shows the dynamics of ions and electrons for the following parameters: length of the system L = 50 cm; magnetic field induction B_0 = 3.3 T. Accelerating field located at a distance of 1 cm in front of the middle plane of the cusp E_z = 0.24 MV/cm. Analogical case with some other parameters is described in details in [5], and is presented here for comparison with the case under consideration, in which the parameters of the accelerated compensated ion beam (CIB) are selected to obtain more suitable ion beam after acceleration and transportation for injecting into the next accelerating unit. In particular, when accelerating field E_z = 1 MV/cm and magnetic field B_0 = 1.1 T (Fig. 2,c), the amplitude of the ion beam corrugation is two times smaller, and the beam is more homogeneous along the z-axis compared to the first case (see Fig. 2,a). The corrugation of the ion beam is associated with the movement of particles in crossed electric and magnetic fields [6].

In the case B_0 = 1.1 T, in order to improve the compensation of the ion beam, the parameters of an additional electron beam (injection location, width, energy) were optimized, that allowed reducing the transverse spread and energy spread of ions at the exit of the drift gap (see Fig. 2,d) compared to the first option ($B_0 = 3.3$ T) (see Fig. 2,b). In both cases, the ion beam acceleration occurs both in the accelerating field and in the field of the space charge of the additional electron beam. However, in the first option (see Fig. 2,b), the main part of the energy of the ion beam is gained in the field of the electron beam (1.5 MeV), rather than in the accelerating field (0.24 MeV), while in the second option (see Fig. 2,d) mostly in the accelerating electric field (1 MeV).

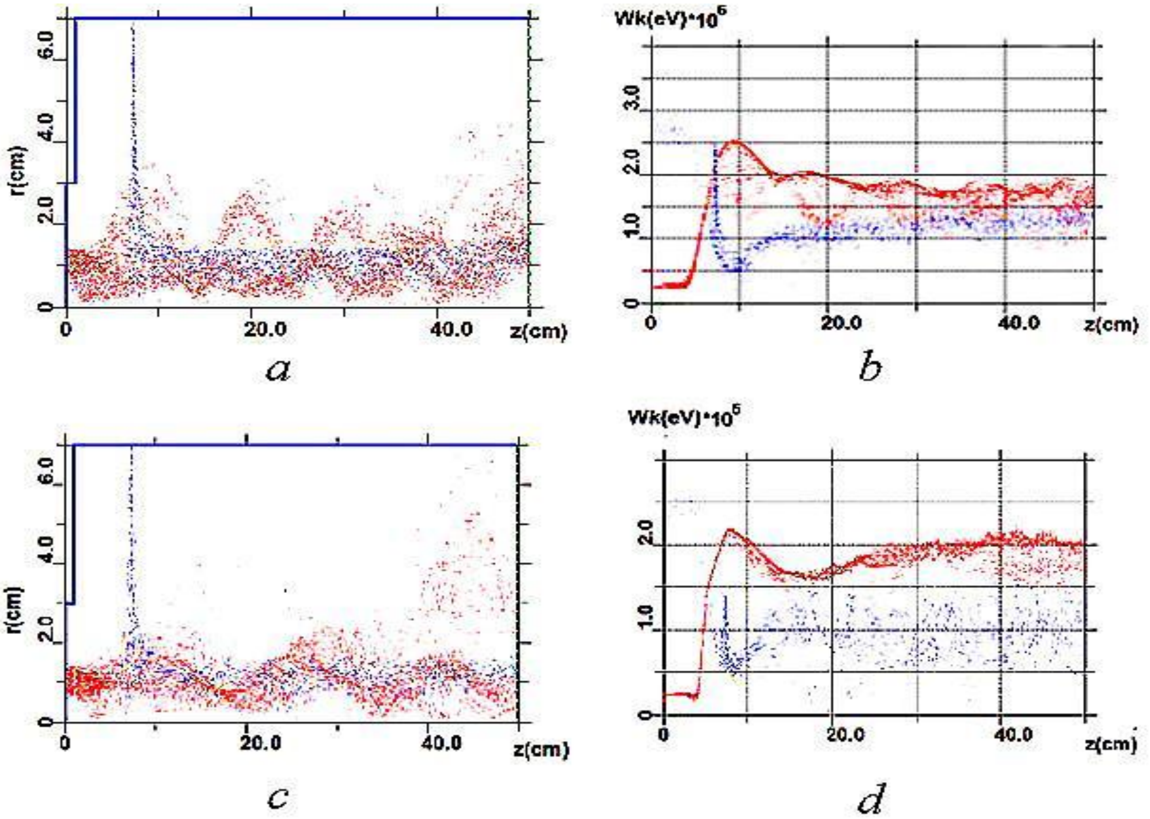

Fig. 2. Arrangement of ion beam (in red), the main electron beam compensating ions up to the second part of cusp, additional electron beam compensating ions after the cusp (in blue), on the rz-plane (a, c). The energy of ion, main and additional electron beams vs the longitudinal coordinate z (b, d). (a, b) – first option, (c, d) – second option. CIB density: $n_i = 10^{12} cm^{-3}$

3. DYNAMICS OF AN ION BEAM IN THE PRESENCE OF A SINGLE ELECTRON BEAM

In the previous section the dynamics of acceleration of the ion beam compensated by the main and additional beams were considered. The main electron beam compensated the ion beam only at the beginning of the cusp, while the additional beam – in the second half of the magnetically insulated gap and in the drift region. However, due to the influence of the accelerating electric field and the space charge field of the additional beam, the main electron beam is locked at the very beginning, reducing its compensating role to a minimum. Therefore, another approach to compensating the ion beam was proposed, when the injection of the main electron beam is absent. It means that the ion beam must pass a short distance without compensation. To achieve this, the magnetically insulated gap was reduced to 5 cm, and the current of the ion beam was selected so that its value was below the critical current at this distance without significant transverse spread so the density of the ion beam remains up to 10^{12} cm^{-3}. The magnetic field induction is taken the same $B_0 = 1.1$ T.

An accelerating field is created at the very beginning of the cusp with a length of 2 cm. Two acceleration options for the ion beam are considered: 1) electric field strength $E_z = 0.5$ MV/cm, 2) $E_z = 1$ MV/cm. From Fig. 3,a, it can be seen that in the first option, without compensation at the beginning of the system, the ion beam diverges significantly, but then, thanks to the electron beam injected radially into the second half of the cusp, it converges towards the axis. As with the presence of two compensating electron beams (see Fig. 2,c), the CIB corrugation is formed, and its amplitude hardly changes (see Fig. 3,a). At the exit of the system, the transverse section of the CIB is close to the initial one, although there is a small number of ions scattered beyond the boundaries. The dynamics of the CIB change slightly in the second option when the accelerating field is higher, $E_z = 1$ MV/cm. In this case, the velocity of the ions in the accelerating gap is higher, so they pass through the area of the cusp without electrons (the first half of the magnetic trap) faster. Therefore, ions receive less impulse expansion under the influence of the volumetric charge compared to the case of a lower accelerating field. Moreover, a faster energy gain by the ion beam due to the continuity of the flow leads to a decrease in its density, and hence, the volumetric charge, which reduces the scattering of ions in the transverse direction. Therefore, the amplitude of the corrugation and the ion beam cross-section decrease (see Fig. 3,d). In both options, the CIB gains energy both in the accelerating field and in the field of the space charge of the electron beam (see Fig. 3,b,e). It should be noted that the accumulation of energy by ions occurs mainly in the accelerating field, both in the first and second cases. Due to the higher value of the accelerating field in the second option, the energy spread of the CIB is smaller (see Fig. 3,f) than in the first option (see Fig. 3,c).

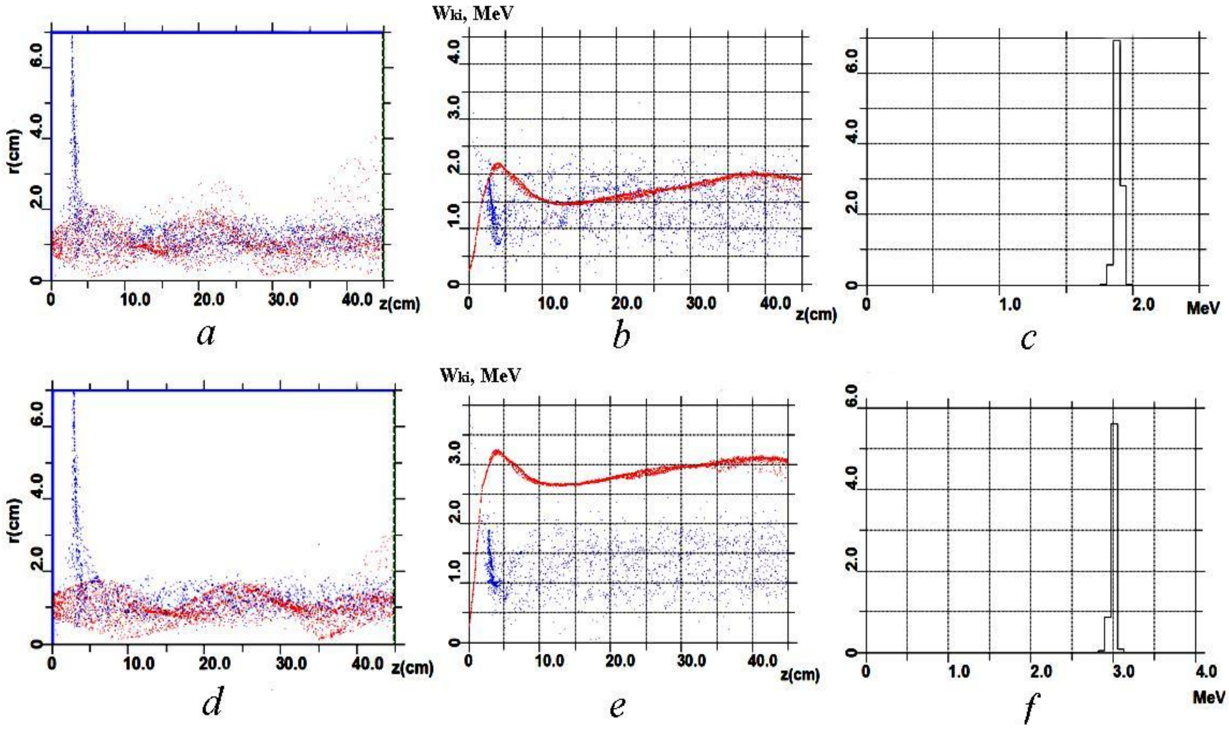

Fig. 3. Arrangement of ion beam (in red), the main electron beam compensating ions up to the second part of cusp, additional electron beam compensating ions after the cusp (in blue), on the rz-plane (a, d). The energy of ion, main and additional electron beams vs the longitudinal coordinate z (b, e). Energy distribution function (c, f) (a, b, c) – E_z = 0.5MB/cm, (d, e, f) – E_z = 1MB/cm. CIB density: $n_i=10^{12} cm^{-3}$

CONCLUSIONS

It has been shown that for all the considered cases, a mono-energetic high-current ion beam injected into a magnetic cusp with an accelerating gap is accelerated, acquires transverse velocity and changes its trajectory in such a way that in the drift region it drifts in the crossed electric field of the spatial charge of the electron and ion beams and external magnetic field, undergoing periodic changes in transverse dimensions along with transverse size variations and loss of mono-energetic properties. Its use for injection into the next analogous section becomes problematic and requires separate study.

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Article received 19.04.2023

ПРИСКОРЕННЯ КОМПЕНСОВАНОГО СИЛЬНОСТРУМОВОГО ІОННОГО ПУЧКА З КАСПОВОЮ МАГНІТНОЮ ІЗОЛЯЦІЄЮ ЕЛЕКТРОНІВ У ПРИСКОРЮЮЧОМУ ЗАЗОРІ ТА ПОДАЛЬШОЮ КОМПЕНСАЦІЄЮ ЕЛЕКТРОННИМ ПУЧКОМ

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2.5D числовим моделюванням досліджено процес магнітної ізоляції електронів і прискорення іонів при інжекції сильноточного іонного пучка, компенсованого електронним пучком, у магнітний касп з прискорюючим зазором і подальшою повторною компенсацією електронним пучком для транспортування в дрейфовій області з однорідним магнітом. Розглянуто залежність характеристик прискореного та скомпенсованого іонного пучка на виході дрейфової області від набору початкових параметрів іонного та електронних пучків та величин магнітного та прискорюючого електричного полів.