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STUDIES OF SPACE-CHARGE NEUTRALIZED ION BEAM INDUCTION LINAC FOR INERTIAL CONFINEMENT FUSION

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Results of theoretical studies and numerical simulations of physical processes in a high-current linear ion induction accelerator (IINDUS) are reported. Nonlinear analytical theory of charge compensation of a high-current ion beam in magnetoinsulated accelerating gaps is presented. The prospects for fusion applications of the proposed accelerators were estimated by means of 2.5-D relativistic electro-magnetic codes which were used for numerical simulation of the processes of ion beam acceleration, charge compensation and stability in the accelerator channel. The results obtained look promising for the chosen direction of research.

1 INTRODUCTION

Recently various schemes have been proposed to produce high-current ion beams (with particle energy $\varepsilon \simeq 1$ GeV and current $I \simeq 10$ kA) by induction fields for inertial confinement fusion devices[1]. One of the promising methods is based on the use of several ion beams transported in vacuum with an injection current of about 1 A and further current increase during acceleration provided by confluence and compression of these non-relativistic beams. Another way of high-current beam production is utilization of collective focusing methods, where ion space-charge strengths are compensated by electrons, as alternative to traditional vacuum transport methods (quadrupoles, solenoids). In order to suppress unwanted electron current, magnetic insulation is used.[2]

Currently induction linacs of the latter type with three to five stages are capable of producing kA ion beams with energies up to several hundred keV.[3–4] It is known, however, that heavy ion fusion (HIF) requires the beam power and brightness to be increased by several orders of magnitude. Therefore, the development of a driver for HIF with a high-current induction linac as a basis involves the investigation of some important physical problems. Results of our previous studies in this direction (see paper[6] and cited references) may be stated as follows:

i) Critical ion beam density n_0 corresponds to a very slight influence of the beam on external magnetic field.

ii) Detailed consideration was given to two most dangerous instabilities that disturb effective ion beam transport through the accelerator channel and the drift chamber: high-frequency beam-plasma instability and electromagnetic filamentation.

iii) For axially symmetric systems a new mechanism of ion beam neutralization in the accelerating gap was proposed.

iv) In an induction linac comprising an injector and two induction stages with magnetoinsulating cusps in the accelerating gaps, the following parameters for space-charge-neutralized beams were obtained: 2 kA, 500 keV, 0.5 μs.

The paper is organized as follows. Nonlinear theory of ion beam neutralization mechanism is presented in Section 2. A numerical model and some features of the electromagnetic relativistic code used for simulations are the contents of Section 3. Results of full-scaled numerical simulations are discussed in Section 4.

2 ION BEAM SPACE-CHARGE COMPENSATION IN THE MAGNETOINSULATED ACCELERATING GAP

In our case the accelerating system is axially symmetric and therefore the well-known mechanism of compensated beam transport through the magnetic barrier[8] does not hold, because in this system azimuthal polarization electric field is absent. Previously[9] we introduced the mechanism of ion beam space-charge neutralization in magneto-insulated accelerating gaps. The basic idea is that a specially injected compensating electron beam drifts through the cusp, owing to the magnetic eigenfield of the ion beam and the radial electric field resulting from the radial separation of the ion and electron beams. It was shown[10,11] that for thin-walled tubular electron and ion beams of equal current densities ($a \gg \Delta$ where a is a radius of the beams and Δ is thickness of their walls) with electron energy higher than accelerating potential difference, the process of space-charge compensation for the time less than ω_i^{-1} and Ω_i^{-1} may be described by a set of equations for scalar potential ϕ and azimuthal magnetic field H_θ. This set of equations is derived from the nonlinear hydrodynamic electron motion equations, written in drift approximation with the retention of the electrical drifts only, the continuity equation, the Maxwell equations for the radial electric field $E_r(r)$ and the azimuthal magnetic field $H_\theta(r)$[10,11]. The equations involved also contain a parametric dependence on the longitudinal coordinate z.

Charge separation potential ϕ is described by following equation

$$\frac{d^2\phi}{dx^2} - \frac{8\pi e\beta n_{0i} v_{0e}\left(\dfrac{m}{2e}\right)^{1/2}}{\left(\dfrac{\varepsilon_{0x}}{e} + \phi(x) - \phi(a)\right)^{1/2}} = -4\pi e n_i(x), \tag{1}$$

$$\phi_{|x=a} = \phi(a), \qquad d\phi/dx_{|x=a} = -E(a),$$

where x is the transverse coordinate, $\beta = n_{0e}/n_{0i}$, n_{0e} and n_{0i} are unperturbed electron and ion densities, $\varepsilon_{0x} = mv_{0x}^2/2$ is the initial value of the transverse electron energy at the internal boundary of the beam, $\phi(a)$ is the value of potential at the inner beam boundary, m and e are the electron mass and charge, and $E(a)$ is the radial electric field intensity inside of the beam. An equation describing a self-consistent magnetic field H_θ has the form

$$\frac{dH_\theta}{dx} - \frac{4\pi e\beta n_{0i}v_{0x}\left(\dfrac{m}{2e}\right)^{1/2} H_\theta \dfrac{d\phi}{dx}}{H_0^2(a)\left(\dfrac{\varepsilon_{0x}}{e} + \phi(x) - \phi(a)\right)^{1/2}} = 4\pi e\frac{v_i}{c}n_i(x), \tag{2}$$

where v_i is the ion beam velocity and $H_0(a)$ is the amplitude of external magnetic field at $x = a$. The region being studied may be divided into two parts:

— At $x < a$ and $x > a + \Delta$ there is no ion beam, but electrons are present.

— At $a \le x \le a + \Delta$ both electrons and ions must be taken into account.

Equations (1) and (2), together with energy and particle flux conservation laws, have been investigated analytically and numerically[11]. In particular, it was shown that the electron drift velocity approaches the value V_{beam} provided that the system parameters satisfy the following conditions:

$$\frac{4\pi n_{0i}\varepsilon_{0x}}{H_0^2(a)} > 1, \qquad 1 \gg \frac{\Delta}{a} \ge \frac{c\Omega_e}{\omega_e^2 a}. \tag{3}$$

Analysis allows one to conclude that charge compensation may be supported by injection of an electron beam accompanying the ion beam in the accelerating system with magnetoisolation. However, the ion beam must have a rather high current in order to raise charge separation field up to necessary values. Note that numerical simulation of the problem with the electromagnetic relativistic 2.5-d particle code confirms the validity of the proposed physical model. (See Section 3.)

3 NUMERICAL SIMULATION OF THE PHYSICAL PROCESSES IN THE INDUCTION LINAC

The self-consistent plasma dynamics in the induction linac is described by the relativistic Vlasov equations for the electron and ion distribution functions and by Maxwell's equations. Numerical simulation of the physical processes in such a system may be performed by the use of a 2-d discrete kinetic model based on the particle-in-cell method for open plasma configurations[12,13], where charged particles are injected into and escape from a bounded computational domain. In the cylindrical frame the problem is two-dimensional, due to the assumption that the functions do not depend on the azimuthal angle θ (while the velocity space has all three dimensions). It is formulated as follows.

Tubular, coaxial electron and ion beams are injected simultaneously in a cylindrical vacuum domain $0 < r < R$, $0 < z < L$ (see Figure 1). All geometrical parameters are the same for the both beams: the beam radius is $a = R/3$, and $\Delta \ll a$. Initial ion and electron temperatures are $T_i = T_e = 0$. The injection velocities are within the range $V_i/c = 0.04 - 0.27$, $V_e/c = 0.81$, with the current-compensation condition being $q_e n_e V_e = q_i n_i V_i$. In the region involved the cusp magnetic field configuration and the ion accelerating potential difference $\Delta\Phi = \Phi_2 - \Phi_1$ are imposed. A similar problem was considered in the Cartesian geometry as well, with the beams being planar and infinite along the z coordinate. In our opinion, cylindrical and Cartesian spatially two-dimensional computations complement each other and enable a comprehensive study of 3-d physical processes in the system. Two-and-a-half-dimensional particle simulations were performed on the grid (256 × 128); the typical number of model particles was $\approx 10^4$ and the mass ratio m_i/m_e was 1840. The following boundary conditions for the EM field were imposed: symmetry at the axis, and a metallic wall for the outer surface. Those for the particles were symmetry at the axis and free escape from

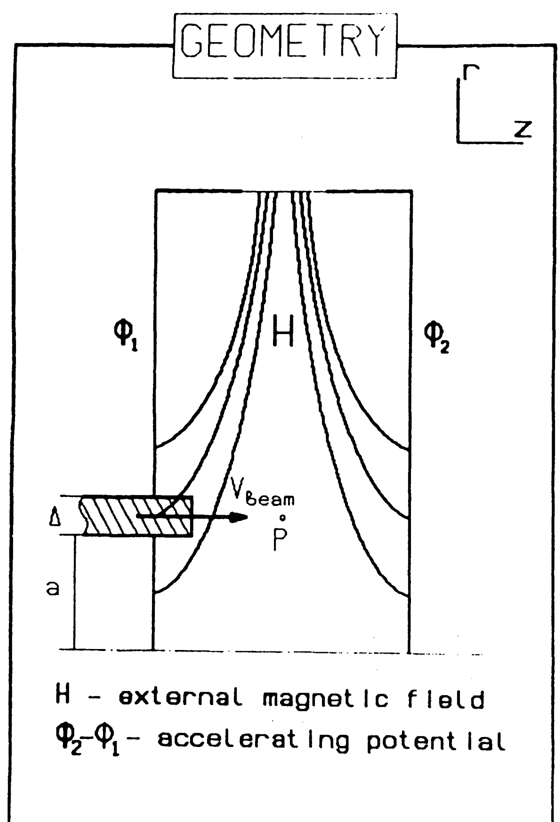

FIGURE 1 Scheme of computational region.

the working region through the external loop (in practice, most of the beam electrons are reflected by the magnetic field and only few of them actually reached the boundary $r = R$). Explicit and half-explicit integration schemes[13,14] were used for solving both the Maxwellian system and the relativistic particle dynamics equations (similar to those used by Boris[14]). The cell dimensions were $\Delta r = \Delta z = 1 \cdot c/\omega_{pe}$ and the time step Δt was $0.1\ \omega_{pe}^{-1}$.

The typical run of some thousand steps, corresponding to several ion transition times $T^i_{TR}(L/V_i \approx 100\ \omega_{pe}^{-1})$, takes a dozen hours of CPU time on an IBM-AT/386 personal computer in standard configuration. We shall mention some prime difficulties encountered in our numerical simulations.

i) Large gradients of the plasma density, caused by space limitation of the beams and associated high level of the HF noise when using the explicit method. The spatial-harmonics filtration suppressed this noise, but due to a small beam thickness we had essential numerical viscosity.

ii) The integration of Ampere's and Faraday's equations without correction procedure for the electric field was difficult to perform, since the radial polarization of the electric field underlies the space-charge compensation mechanism under consideration.

iii) Subrelativistic electron velocities imposed strict conditions on the accuracy of the integration and calculation of the equations of motion. In the electrostatical approximation, the unlimited increase of azimuthal electron momentum that led to computational errors in relativistic factor determination may cause spurious electron drift in the z-direction even if the condition of Eq. (3) is violated. But when a self-consistent magnetic field is taken into account, this false effect disappears because the increase of azimuthal current leads to the violation of magnetic insulation, which stops further growth of electron momentum in the azimuthal direction. The algorithm, based on time centering, assumes the determination of currents at integer moments of time. In the literature[15] different ways were proposed to interpolate the current from particles to grid. The dependence of results on the choice of algorithm under identical approximating properties was noted.

In the present calculations, on determining the current (as an average, $2j = j^{+\tau/2} + j^{-\tau/2}$) we found the effect of the thin virtual anode formation near the beam injector: the electrons were reflected back within 2–3 τ and, in the computational region, a great positive charge was accumulated. This led to the separation of the ions into passing and reflected ones (see Figure 2).

The abovementioned difficulties led us to the development of half-implicit methods with the filtration, which gave satisfactory results presented below.

4 COMPUTATIONAL RESULTS

Numerical calculations were mainly intended to prove the validity of the charge-compensation mechanism suggested above. Particle spatial distribution, obtained during the simulation with the magnetic field **H**, satisfying Eq. (3) and with $\Phi_2 =$

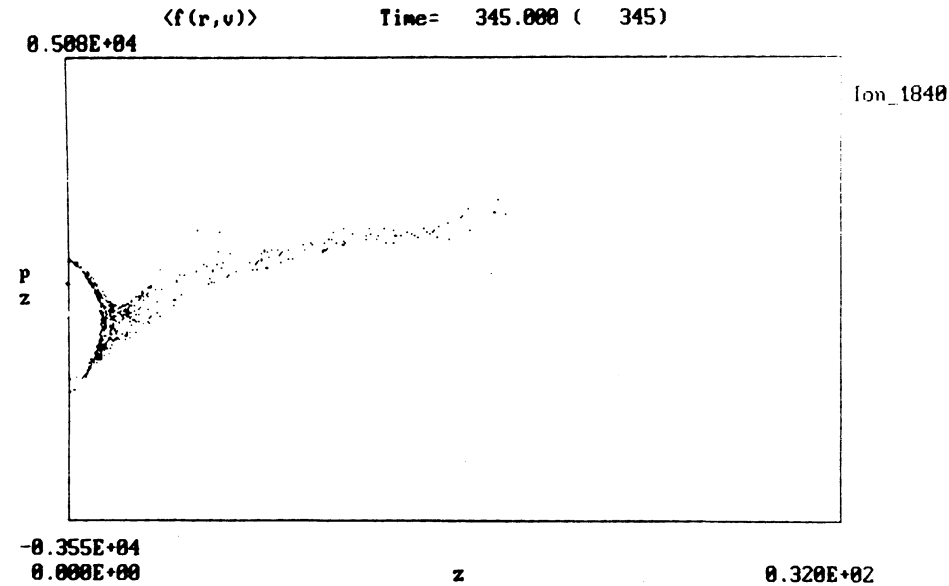

FIGURE 2 Projection of ion distribution function on (pz-z) plane. When ion beam energy is too small for computational grid to resolve the Debuy (scintillation) length, numerical boundary condition may cause a spurious virtual anode. The figure shows that ion beam fails to pass the left part of the region.

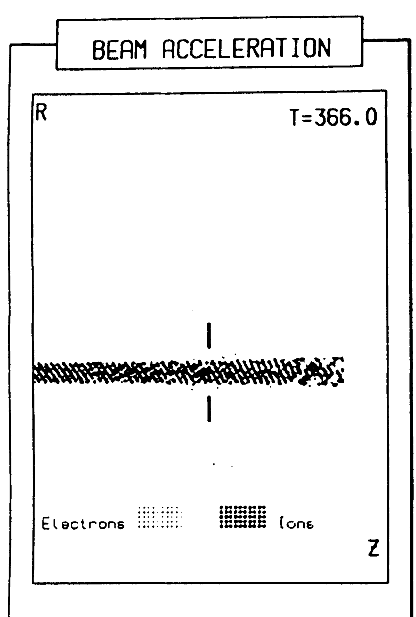

FIGURE 3 Projection of particle distribution functions on the (r–z) plane. When the conditions at Eq. (3) are met, both electron and ion beams pass through magnetic insulation, providing space-charge neutralization.

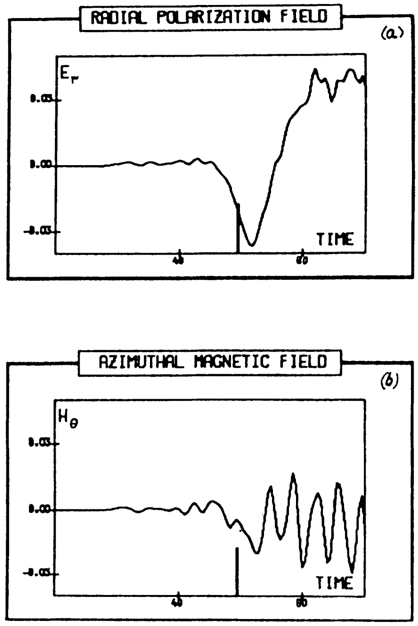

FIGURE 4a,b Time dependence of radial polarization field and azimuthal magnetic field at the center of the cusp (point P in Figure 1). Solid vertical lines denote the ion half-transition time. Correct direction of electron drift at the beam front is provided by the product $E_r \cdot H_0$.

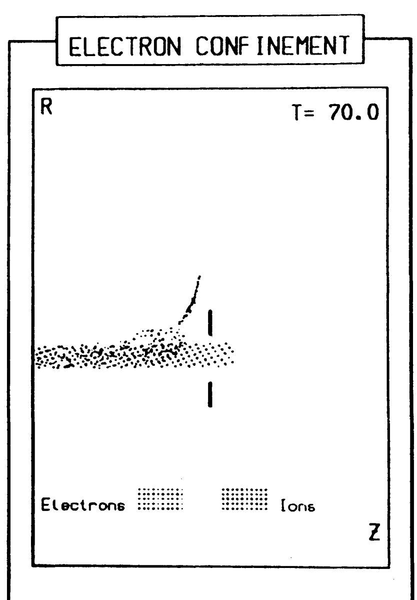

FIGURE 5 Projection of particle distribution functions on the (r–z) plane. When the external magnetic field is stronger than the conditions of Eq. (3) prescribe, the electron beam is unable to neutralize ions behind the magnetic insulation.

$\Phi_1 = 0$, is presented in Figure 3. It may be seen that the main portion of the electron beam is passing through the middle of the cusp, marked by two vertical lines, due to the drift mechanism. The main contribution to the drift velocity is given by the product of the azimuthal magnetic field H_θ and the radial polarization field E_r components. Figures 4a and 4b show the time dependence of these field components measured at the point P (see Figure 1). A vertical dash at the time axis indicates the ion half-transition time $T^i_{TR}/2$. As can be seen from the figures, positive z-drift in the middle of the cusp is provided by increasing negative values of both fields involved by the moment $T^i_{TR}/2$. Note that the electrons pass the cusp center at a velocity of about the ion beam speed. The last circumstance is particularly important for further ion beam compensation. Approximately at $t > 2/3 \cdot T^i_{\mathrm{TR}}$ a quasi-stationary regime sets in. Being unmagnetized and more inertial, the ions have straight trajectories, except for the small front part of them, which is expanding in the absence of charge compensation.

When the external magnetic field is stronger than the condition of Eq. (3) prescribes, the electrons trace magnetic lines because they cannot be pulled through the cusp. The seris of calculations of the linac operation in the acceleration regime, with the accelerating voltage assigned by the condition $\Phi_1 = 0$, $\Phi_2 = 0.5 \cdot m_3 c^2$, gave reasonably good results.

Thus, the simulations performed confirm the principal possibility of heavy ion acceleration with the use of the technique described above. Note that some instabilities occurred in the simulations. A substantial part of them were of numerical nature. The study of the beam-plasma instabilities, occurring or being likely to occur in such a system, as well as the development of a reasonably adequate model of the induction linac, are the subjects of further investigations.

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