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Ion beam pulse neutralization by a background plasma in a solenoidal magnetic field

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Abstract

Ion beam pulse propagation through a background plasma in a solenoidal magnetic field has been studied analytically. The neutralization of the ion beam current by the plasma has been calculated using a fluid description for the electrons. This study is an extension of our previous studies of beam neutralization without an applied magnetic field. The high solenoidal magnetic field inhibits radial electron transport, and the electrons move primarily along the magnetic field lines. For high-intensity ion beam pulses propagating through a background plasma with pulse duration much longer than the electron plasma period, the quasi-neutrality condition holds, $n_e = n_b + n_p$, where n_e is the electron density, n_b is the density of the ion beam pulse, and n_p is the density of the background plasma ions (assumed unperturbed by the beam). For one-dimensional electron motion, the charge density continuity equation $\partial\rho/\partial t + \nabla\cdot\mathbf{j} = 0$ combined with the quasi-neutrality condition $[\rho = e(n_b + n_p - n_e) = 0]$ yields $\mathbf{j} = 0$. Therefore, in the limit of a strong solenoidal magnetic field, the beam current is completely neutralized. Analytical studies show that the solenoidal magnetic field starts to influence the radial electron motion if $\omega_{ce} \geqslant \omega_{pe}\beta$ (where $\omega_{ce} = eB/mc$ is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and $\beta = V_b/c$ is the ion beam velocity relative to the speed of light). This condition holds for relatively small magnetic fields. For example, for a 100 MeV, 1 kA Ne^+ ion beam ($\beta = 0.1$) and a plasma density of $10^{11}\,\mathrm{cm}^{-3}$, B corresponds to a magnetic field of 100 G.

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1. Ion beam neutralization in a background plasma without external magnetic field

Ion beam pulses are used in many applications, including heavy ion inertial fusion [1–3] high-density laser-produced proton beams for fast

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ignition of inertial confinement fusion targets [4], positron beams for electron–positron colliders [5], etc. To neutralize a large repulsive space-charge force of the ion beam charge, the ion beam pulses can be transported through a background plasma. The plasma electrons can effectively neutralize the ion beam charge, and the background plasma can provide an ideal medium for ion beam transport and focusing. Because the detailed parameter values for heavy ion fusion drivers are not well prescribed at the present time, an extensive study is necessary for a wide range of beam and plasma parameters to determine the conditions for optimum beam propagation.

The electron response time to an external charge perturbation is determined by the electron plasma frequency, $\omega_{pe} = (4\pi n_p e^2/m_e)^{1/2}$, where n_p is the background plasma density. Therefore, as the beam pulse enters the background plasma, the plasma electrons tend to neutralize the ion beam on a time scale of order $\tau_{pe} \equiv 1/\omega_{pe}$. Typically, the ion beam pulse propagation duration through the background plasma is long compared with τ_{pe}. As a result, after the beam pulse passes through a short transition region, the plasma disturbances are stationary in the beam frame. We have developed reduced nonlinear models, which describe the stationary plasma disturbance (in the beam frame) excited by the intense ion beam pulse [6]. In recent calculations [7,8], we have studied the nonlinear quasi-equilibrium properties of an intense, long ion beam pulse propagating through a cold, background plasma, assuming that the beam pulse duration τ_b is much longer than τ_{pe}, i.e., $\omega_{pe}\tau_b \gg 1$. In the study reported in Ref. [9], we extended the previous results to general values of the parameter $\omega_{pe}\tau_b$. The key assumption in these papers is that the electron thermal velocity (V_{Te}) can be neglected, because it is much smaller than the ion beam velocity (V_b). The typical electron temperature of the background plasma is a few eV, and the condition $V_{Te} \ll V_b$ is satisfied for sufficiently fast ion beams with velocity $V_b \gg 0.01c$. This assumption allowed us to use the fluid approximation and obtain an analytical solution for the self-electric and self-magnetic fields of the ion beam pulse. Theoretical predictions agree well with the results of calculations utilizing a particle-in-cell (PIC) code [7–9].

The model predicts very good charge neutralization during quasi-steady-state propagation, provided the beam is nonrelativistic and the beam pulse duration τ_b is much longer than the electron plasma period $2\pi/\omega_{pe}$, independent of the ion beam current. However, the degree of beam current neutralization depends on the background plasma density and the ion beam current. The ion beam current is neutralized by the electron current, provided the beam radius is large compared with the electron skin depth c/ω_{pe}. This condition can be written as

$$I_b > 4.25\beta n_b/n_p kA. \quad (1)$$

For the parameters characteristic of heavy ion fusion drivers, the condition in Eq. (1) holds [3,6], whereas for present scaled experiments condition (1) does not hold [2]. In Ref. [10], it was proposed that the unneutralized electrostatic electric field is reduced by the background plasma to potential values of order

$$\phi_0 = m_e V_b^2/2. \quad (2)$$

This potential accelerates the plasma electrons up to the ion beam velocity. Analytical and numerical studies [7,9,11] show that the potential in Eq. (2) emerges at the end boundary of a neutralization section as the beam exits this section. The neutralization section may consist of an electron-emitting electrode, a biased foil, or a short plasma plug without any background plasma during further ion beam propagation.

The estimate in Eq. (2) does not pertain to neutralization by an extended background plasma when the beam pulse is immersed inside the plasma. In the latter case, the longitudinal electric field is predominantly inductive, and in the laboratory frame it is described by the vector potential $\mathbf{A} = A_z\mathbf{e}_z$ rather than the electrostatic potential. The radial electric field is determined from the equivalent electrostatic potential

$$\phi = m_e V_e^2/2, \quad (3)$$