ION BEAM PULSE INTERACTION WITH BACKGROUND PLASMA IN A SOLENOIDAL MAGNETIC FIELD*

Igor D. Kaganovich#, Edward A. Startsev, Ronald C. Davidson
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

Abstract

Background plasma can be used as an effective neutralization scheme to transport and compress intense ion beam pulses, and the application of a solenoidal magnetic field allows additional control and focusing of the beam pulse. Ion beam pulse propagation in a background plasma immersed in an applied solenoidal magnetic field has been studied both analytically and numerically with three different particle-in-cell codes (LSP, OOPIC-Pro and EDPIC) to cross-check the validity of the results. Very good charge and current neutralization is observed for high values of the solenoidal magnetic field. However, for intermediate values of the solenoidal magnetic field, current neutralization is a complex process, and a sizable self-magnetic field is generated at the head of the beam. Collective wave excitations are also generated ahead of the beam pulse.

Neutralization of the ion beam charge and current by a background plasma is an important issue for many applications involving the transport of positive charges in plasma, including heavy ion inertial fusion [1,2,3], positrons for electron-positrons colliders [4], intense laser-produced proton beams for the fast ignition of inertial confinement fusion targets [5], etc.

To neutralize the large repulsive space-charge force of the ion beam, 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. There are many critical parameters for ion beam transport in the target chamber, including beam current, type of ion species, radial and longitudinal profiles of the beam density, chamber gas density, stripping and ionization cross sections, etc. 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.

To complement the numerical simulation studies, a number of reduced models have been developed. Based on well-verified assumptions, reduced models can yield robust analytical and numerical descriptions and provide important scaling laws for the degrees of charge and current neutralization [6].

The electron response time to an external charge perturbation is determined by the electron plasma frequency, $\omega_{pe} = \left(4\pi n_p e^2 / m_e\right)^{1/2}$, where n_p is the background plasma density. Therefore, as the ion 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. 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 $\omega_{pe}\tau_b$. Theoretical predictions agree well with the results of calculations utilizing several particle-in-cell (PIC) codes [see Refs. 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 $2\pi/\omega_{pe}$, i.e., $\omega_{pe}\tau_b \gg 2\pi$. Thus, the degree of charge neutralization depends on the beam pulse duration and plasma density and is independent of the ion beam current (if $n_p > n_b$).

However, the degree of ion beam current neutralization depends on both the background plasma density and the ion beam current. The ion beam current can be neutralized by the electron return current. The ion beam charge is neutralized mostly by the action of the electrostatic electric field. In contrast, the electron return current is driven by the inductive electric field generated by the inhomogeneous magnetic flux of the ion beam pulse in the reference frame of the background plasma. Electrons are accelerated in the direction of beam propagation, thus the electrons tend to neutralize the current as well as the charge. The inductive electric field penetrates into the plasma on distances of order the skin depth c/ω_{pe}. If the beam radius r_b is small compared with the skin depth $r_b < c/\omega_{pe}$, the electron return current is distributed over distances of order c/ω_{pe}. As a result, the electron return current is about $\omega_{pe} r_b / c$ times smaller than the ion beam current. Consequently, 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}, i.e., $r_b > c/\omega_{pe}$, and is not neutralized in

*Research supported by the US Department of Energy.
#ikaganov@pppl.gov

the opposite limit. This condition can be written as $I_b > 4.25(\beta n_b / n_p)kA$ [8], where βc is the directed beam velocity. Figure 1 shows the good charge neutralization for $\omega_{pe}\tau_b = 60$. At the head and tail of the beam pulse $r_b < c/\omega_{pe}$, and the ion beam current is not neutralized. In the central region of the pulse $r_b > c/\omega_{pe}$,

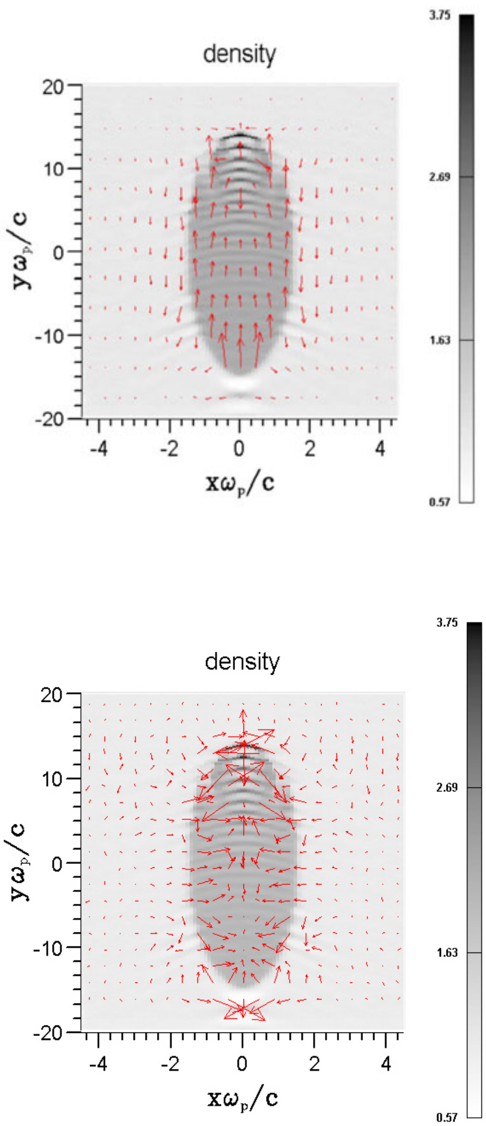

Figure 1. Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma, calculated using the EDPIC code [7]. The beam propagates in the y-direction. The beam density has a flat-top profile with sharp edges. Shown in the figure are color plots of the normalized electron density (n_e/n_p). The beam velocity is $V_b=0.5c$, and the beam density is $n_b=0.5n_p$. The beam dimensions correspond to $r_b=1.5\,c/\omega_p$ and $\omega_{pe}\tau_b = 60$. Red arrows show vector fields corresponding to: the total current (top), and $-e\mathbf{E}$ - the force acting on the electrons to pull electrons inside the beam (bottom).

and the ion beam current is well neutralized. We have also studied how quickly the steady-state equilibrium is reached after the ion beam enters the plasma region [10]. The transition region depends on the boundary conditions and on the plasma dimensions. If there is no electron emission from the plasma boundaries, and the plasma's radial dimension is comparable with the ion beam radius, electron holes form near the plasma boundaries across the beam, because the ion beam pulls electron radially from the sides. Interestingly, these electron holes move relative to the ion beam with a speed which is a fraction of the ion beam speed. Thus, the electron holes lag the ion beam pulse and eventually leave the simulation box [10].

During the entry into the plasma of an intense ion beam pulse with density larger than the plasma density, more complex electron response is observed, as shown in Fig.2. Visualizations (movies) of these processes are available in supplementary documents to Refs.[10, 11]. At later times than shown in Fig.2, electron holes are formed inside the beam.

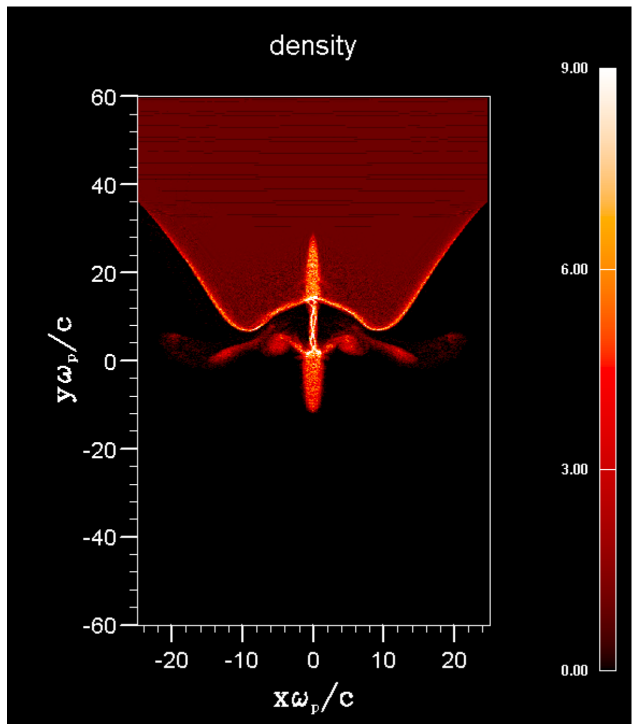

Figure 2. Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma (similar to Fig.1, but the beam density is $n_b=5n_p$). The beam dimensions correspond to $r_b=0.5\,c/\omega_p$ and $\omega_{pe}\tau_b = 120$.

In addition, we have studied influence of an externally applied solenoidal magnetic field on degree of the charge and current neutralization both analytically and numerically. The applied magnetic field is directed along the ion beam velocity. Analytical studies show that the solenoidal magnetic field starts to influence the radial electron motion when $\omega_{ce} \geq \omega_{pe}\beta$ [12]. If $\omega_{ce} \ll \omega_{pe}\beta$, the applied magnetic field does not influence the degree of charge and current neutralization relative to the unmagnetized case. The opposite condition $\omega_{ce} \geq \omega_{pe}\beta$ already holds for relatively small magnetic fields: for example, for a 100MeV, 1kA Ne^{+} ion beam (β=0.1) and plasma density of 10^{11}cm^{-3}, the condition $\omega_{ce} = \omega_{pe}\beta$ corresponds to a magnetic field of only 100G.

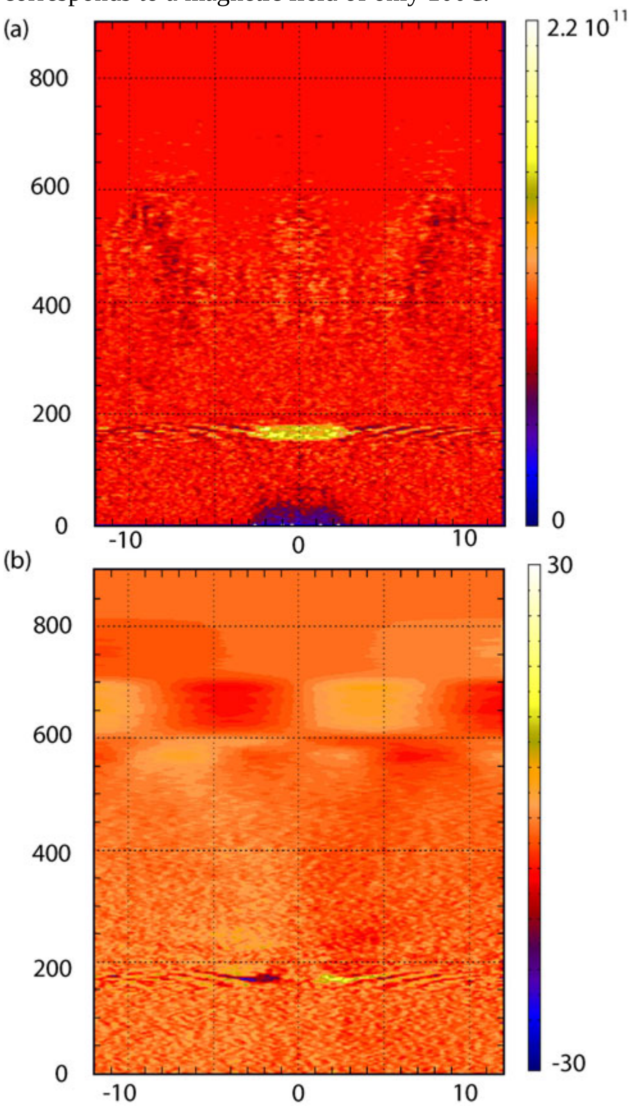

Figure 3. The charge and current neutralization of the ion beam pulse is calculated in two-dimensional slab geometry using the LSP code [13] for the magnetic field strength corresponding to ω_{ce}/ω_{pe}=5.6. The background plasma density is n_p=10^{11}cm^{-3}. The beam velocity is V_b=*0.2c*; the beam current is 1.2kA (48.0A/cm^2), which corresponds to the ion beam density n_b=0.5n_p; and the ion beam charge state is $Z_b = 1$. The beam dimensions (r_b=2.85cm and τ_b=1.9 ns) correspond to a beam radius r_b=1.5c/ω_{pe}, and pulse duration $\tau_b\omega_{pe} = 75$. The solenoidal magnetic field 1014G corresponds to $\omega_{ce} = \omega_{pe}$. Shown are color plots of the electron density (top) and the magnetic field component B_y generated by the ion beam pulse (bottom).

In the limit $\omega_{ce} \gg \omega_{pe}\beta$, the electron return current completely neutralizes the ion beam current. A small unneutralized current j is associated with the remnant radial electron transport across the magnetic field and is proportional to $(\omega_{ce}/\omega_{pe}\beta)^{-2}$.

Plasma waves generated by the beam head are greatly modified when $\omega_{ce} > \omega_{pe}\beta$ and become whistler waves, in which the electron density perturbations are coupled with magnetic perturbations [12]. Application of an external solenoidal magnetic field leads to the excitation of whistler waves at the beam entry into the plasma, as shown in Fig.3. Application of an external solenoidal magnetic field clearly makes the collective processes in ion beam-plasma interaction considerably more complex and rich in physics content.

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