

## TRANSPORT OF INTENSE BEAM PULSES THROUGH BACKGROUND PLASMA

I. D. Kaganovich, A. B. Sefkow, E.A. Startsev, and R.C. Davidson\*

<sup>1</sup>*Plasma Physics Laboratory, Princeton, NJ 08543 USA*

This paper presents a survey of the present numerical modelling techniques and theoretical understanding of plasma neutralization of intense particle beams. For IFE it is critical to develop a basic understanding of the conditions for quiescent beam propagation over large distances, controlling pinching and filamentation effects, and minimizing the degradation of beam quality due to instabilities and particle loss. We previously developed a reduced analytical model of beam charge and current neutralization for an ion beam pulse propagating in a cold background plasma [1,2, 3]. The model made use of the conservation of generalized fluid vorticity. The predictions of the analytical model agree very well with numerical simulation results. The model predicts very good charge neutralization during quasi-steady-state propagation, provided the beam pulse duration is much longer than the electron plasma period. In the opposite limit, the beam pulse excites large-amplitude plasma waves. If the beam density is larger than the background plasma density, the plasma waves break, which leads to electron heating. The reduced-fluid description provides an important benchmark for numerical codes and yields useful scaling relations for different beam and plasma parameters. This model has been extended to include the additional effects of a solenoidal magnetic field, gas ionization and the transition regions during beam pulse entry and exit from the plasma [4]. Analytical studies show that a sufficiently large solenoidal magnetic field can increase the degree of current neutralization of the ion beam pulse. However, simulations also show that the self-magnetic field structure of the ion beam pulse propagating through background plasma can be complex and non-stationary [5]. Plasma waves generated by the beam head are greatly modified, and whistler waves propagating ahead of the beam pulse are excited during beam entry into the plasma. Accounting for plasma production by gas ionization yields a larger self-magnetic field of the ion beam compared to the case without ionization, and a wake of the current density and self-magnetic field are generated behind the beam pulse. Beam propagation in a dipole magnetic field configuration and background plasma has also been studied [3].

Space-charge-dominated ion beam pulses for warm dense matter and heavy ion fusion applications must undergo simultaneous transverse and longitudinal compression in order to reach the desired high-beam intensities at the target. Longitudinal focusing is achieved by

imposing an axial velocity tilt on the beam and subsequently neutralizing its space-charge and current in a drift region filled with high-density plasma. A strong solenoid (multi-Tesla) near the end of the drift region to transversely focus the beam to a submillimeter spot size coincident with the longitudinal focal plane is modelled. The neutralization provided by the background plasma is critical in determining the total achievable compression of the beam pulse. Long-time and large-space-scale plasma flow simulations indicate that adequate plasma densities can be provided throughout the drift region for ion beam charge neutralization in near-term focusing experiments.

The application of a small solenoidal magnetic field can drastically change the self-magnetic and self-electric fields of the beam pulse, thus allowing effective control of the beam transport through the background plasma [4]. An analytical model was developed to describe the self-magnetic field of a finite-length ion-beam pulse propagating in a cold background plasma in a solenoidal magnetic field. The analytical studies show that the solenoidal magnetic field starts to influence the self-electric and self-magnetic fields when  $\omega_{ce} > \omega_{pe}\beta_b$ , where  $\omega_{ce} = eB/mc$  is the electron gyrofrequency,  $\omega_{pe}$  is the electron plasma frequency, and  $\beta_b$  is the ion-beam velocity relative to the speed of light. Theory predicts that when  $\omega_{ce} \sim \omega_{pe}\beta_b$  there is a sizable enhancement of the self-electric and self-magnetic fields due to the dynamo effect [4]. This threshold value of the solenoidal magnetic field is relatively small for nonrelativistic beams.

The dynamo effect occurs due to the electron rotation, which twists the applied magnetic field and generates a self-magnetic field that is much larger than in the limit with no applied magnetic field. Another effect is the generation of a large radial electric field. Because in a steady state the  $v \times B$  force should be balanced by a radial electric field, the electron rotation results in a plasma polarization and produces a much larger self-electric field than in the limit with no applied magnetic field. The third unexpected effect is that the joint system consisting of the ion-beam pulse and the background plasma act as a paramagnetic medium, i.e., the solenoidal magnetic field is enhanced inside of the ion-beam pulse. For larger values of the solenoidal magnetic field, the beam can generate whistler and lower-hybrid waves. In the presence of the solenoidal magnetic field, the radial force acting on the beam ions can change sign from focusing to defocusing, because the radial electric field increases more rapidly than the magnetic force, as the solenoidal magnetic field increases, as shown in Figure 1.

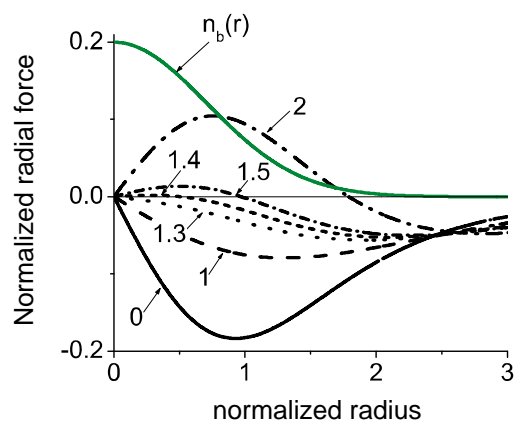


Figure 1. The normalized radial force acting on the beam particles for different values of the parameter  $(\omega_{ce}/\omega_{pe}\beta_b)^2$ . The green curve shows the Gaussian density profile multiplied by 0.2 in order to fit the profile into the plot. The beam radius is equal to the skin depth in the figure.

A possibility of beam steering by utilizing a dipole magnet in plasma has been studied in large scale particle-in-cell simulations [3]. It was shown that in 2D simulations the beam is not neutralized due to electron attachment to magnetic field lines. In 3D simulations, electrons can neutralize the beam by flowing along field lines. However, quadruple-like structure of the electric field appears due to  $\mathbf{v} \times \mathbf{B}$  drifts, as shown in Fig.2. An effect of this electric field on the beam emittance has to be yet investigated in future studies.

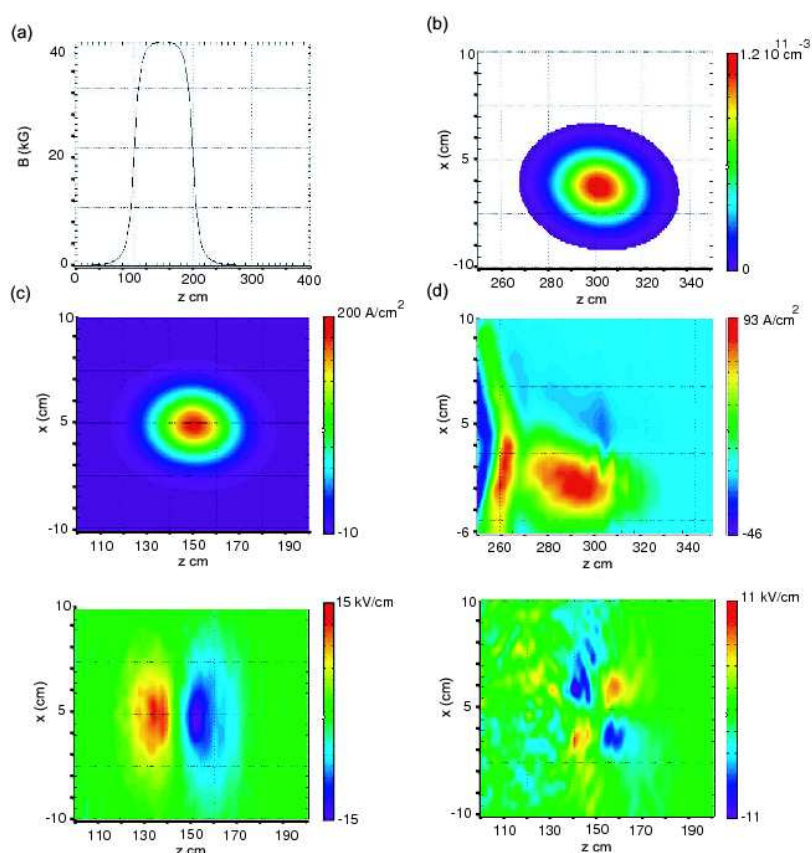


Figure 2. Beam propagation in a dipole magnetic field. Plots correspond to: (a) the magnetic field of the dipole,  $B_y$ ; (b) the beam density in the dipole region; (c) the current density in the dipole region,  $j_z$ ; (d) the current density outside the dipole region,  $j_z$ ; (e) the longitudinal, inductive electric field,  $E_z$ ; and (f) the

transverse electric field,  $E_x$ . The beam and plasma parameters are The background plasma density is  $n_p=10^{11}\text{cm}^{-3}$ . The beam velocity is  $V_b=0.2c$ ; the beam current is 1.2kA ( $48.0\text{A}/\text{cm}^2$ ), 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 ( $r_b=2.85\text{cm}$  and  $\tau_b=1.9\text{ ns}$ ) correspond to a beam radius  $r_b=1.5 c / \omega_{pe}$ , and pulse duration  $\tau_b \omega_{pe} = 75$ .

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