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Effects of finite pulse length, magnetic field, and gas ionization on ion beam pulse neutralization by background plasma

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Abstract

This paper presents a survey of the present theoretical understanding of plasma neutralization of intense heavy ion beams. Particular emphasis is placed on determining the degree of charge and current neutralization. We previously developed a reduced analytical model of beam charge and current neutralization for an ion beam pulse propagating in a cold background plasma. 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. 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. 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.

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1. Introduction

The neutralization of the ion beam space 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 fusion [1–4], positrons for electron–positron colliders [5], intense laser-produced proton beams for the fast ignition of inertial confinement fusion targets [6], production of charge-compensated intense proton beams in an accelerating ring at currents above the space-charge limit [7], etc.

To neutralize the large repulsive space-charge force of an intense ion beam, the 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, including beam current, type of ion species, transverse and longitudinal profiles of the beam density, gas density, stripping and ionization cross-sections, etc. Because detailed beam and plasma parameter

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values are not always well prescribed, an extensive study is necessary for a wide range of beam and plasma parameters to determine the conditions for optimum beam propagation and focusing [8]. To complement the numerical simulation studies, a number of reduced theoretical 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 [9–11]. The initial designs for ion beam propagation in the target chamber invoked unneutralized beam transport. However, due to the large space-charge and possible gas and vapor presence in the chamber, neutralized beam transport appears to be a more practical option. An intense ion beam pulse that has considerable ion charge attracts electrons from the ambient plasma background, producing incomplete charge neutralization. The incomplete neutralization results in nonlinear, uncontrollable forces on an ion beam pulse, which inhibit focusing to a small spot size. Therefore, nearly complete charge neutralization of the ion beam pulse appears to be the only practical solution for ballistic focusing of intense ion beam pulses.

This paper presents a survey of the present theoretical understanding of the neutralization of intense heavy ion beams by background plasma. The organization of the paper is as follows: Section 2 discusses disadvantages of the plasma plug scheme for beam neutralization, Section 3 identifies the key plasma parameters for good charge and current neutralization of the ion beam pulse, Section 4 highlights the main results of nonlinear reduced analytical models describing the degree of charge and current neutralization by background plasma, and Sections 5–7 describe the effects of a solenoidal magnetic field, gas ionization, and a dipole magnetic field, respectively, on the self-electric and self-magnetic fields of an ion beam pulse propagating in a background plasma.

2. Disadvantages of plasma plug scheme for beam neutralization

Previous studies have explored the option of ion beam pulse neutralization by passing the beam pulse though a layer of plasma or a plasma plug [3,4,12–14,19]. The ion beam pulse extracts electrons from the plasma plug and drag electrons along its motion outside the plasma plug region. There are several limitations of this scheme. When the intense beam pulse enters the plasma, the electrons stream into the beam pulse in the strong self-electric and magnetic fields, attempting to drastically reduce the ion beam space charge from unneutralized to a completely neutralized value.

During the entry into the plasma of an intense ion beam pulse with density larger than the background plasma density, a very complex electron response is observed, as shown in Fig. 1. Visualizations (movies) of these processes are available in the supplementary documents to Refs. [11,15]. A current of back-streaming electrons

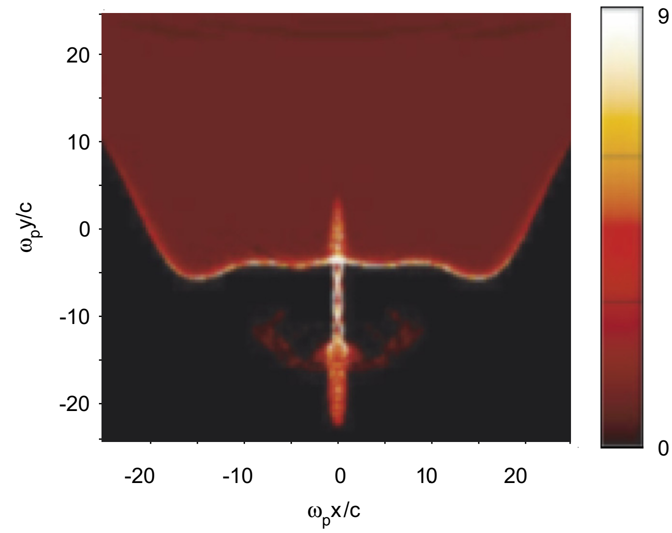

Fig. 1. Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma, calculated using the EDPIC code [9]. The beam propagates in the y-direction. Shown in the figure is the color plot of the normalized electron density (n_e/n_p). The beam velocity is $V_b = 0.5c$, and the beam density is $n_b = 5n_p$. The beam dimensions correspond to $r_b = 0.5c/\omega_{pe}$ and $\omega_{pe}\tau_b = 120$, where τ_b is the pulse length.

develops as the unneutralized beam pulse approaches the plasma. This electron current is comparable with the ion beam current and produces a strong self-magnetic field, leading to some hosing effects as shown in Fig. 1. This current flows near the beam axis and results in a nonlinear space-charge force and a substantial beam emittance growth during beam entry into the plasma. At later times than shown in Fig. 1, electron holes are formed inside the beam pulses, which slowly disappear at later times, as shown in the movies in Refs. [11,15].

This process can be violent and complex, as shown in the visualizations in Refs. [11,15,16]. 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 transverse dimension is comparable with the ion beam radius, electron holes form near the plasma boundaries across the beam, because the ion beam pulls electrons in radially from the transverse directions. 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}. However, the electron holes exist for a very long time, much longer than the plasma period τ_{pe}, as one would initially expect [17]. Interestingly, these electron holes move relative to the ion beam pulse with a speed that is a fraction of the beam speed. Thus, the electron holes lag the ion beam pulse and eventually leave the simulation box [11,16].