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Effects of beam-plasma instabilities on neutralized propagation of intense ion beams in background plasma ☆

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ABSTRACT

The streaming of an intense ion beam relative to background plasma can cause the development of fast electrostatic collective instabilities. The plasma waves produced by the two-stream instability modify the ion beam current neutralization and produce non-linear average forces which can lead to defocusing of the ion beam. Recently, a theoretical model describing the average de-focusing forces acting on the beam ions has been developed, and the scalings of the forces with beam-plasma parameters have been identified (Startsev et al. in press[1]). These scalings can be used in the development of realistic ion beam compression scenarios in present and next-generation ion-beam-driven high energy density physics and heavy ion fusion experiments. In this paper the results of particle-in-cell simulations of ion beam propagation through neutralizing background plasma for NDCX-II parameters are presented. The simulation results show that the two-stream instability can play a significant role in the ion beam dynamics. The effects of velocity tilt on the development of the instability and ion beam compressibility for typical NDCX-II parameters are also simulated. It is shown that the two-stream instability may be an important factor in limiting the maximum longitudinal compression of the ion beam.

1. Introduction and theoretical model

In ion-beam-driven high energy density physics and heavy ion fusion applications, the intense ion beam pulse propagates through a background plasma before it is focused onto the target [1,2]. The streaming of the ion beam relative to the background plasma can cause the development of fast electrostatic collective instabilities [3]. These instabilities produces fluctuating electrostatic fields that cause a significant drag on the background plasma electrons and can accelerate electrons up to the average ion beam velocity. Consequently, the dominant electron current can reverse the beam self-magnetic field. As a result, the magnetic self-field force reverses sign and contributes to a transverse defocusing of the beam ions, instead of a pinching effect in the absence of instability [4,5]. In addition, the ponderomotive force of the unstable waves push background electrons transversely away from the unstable region inside the beam, which creates an ambipolar electric field, which also leads to ion beam transverse defocusing. Because the instability is resonant it is strongly affected and thus can be effectively mitigated and controlled by the longitudinal focusing of the ion beam [6–8].

Two-stream collective interactions between the beam ions and plasma electrons excite unstable waves with phase velocity ω/k_z slightly below the ion beam velocity v_b. Here ω is the unstable wave frequency and k_z is the unstable wave longitudinal wave-number (along the beam propagation direction z). In a recent publication [1] we have studied the nonlinear effects of a developed two-stream instability on a non-relativistic heavy ion beam with ions of mass m_b, charge $q=Z_be$, density n_b, and longitudinal velocity $v_b \ll c$ during its propagation through cold neutralizing background plasma with density n_p and with no externally applied magnetic field. Here c is the speed of light. There, we developed a model that qualitatively captures the main nonlinear features that have been observed in numerical simulations of a proton beam propagating through a dense plasma background, and provides order-of-magnitude estimates of the average forces acting on the beam ions, provided that $Z_bn_b/n_p \ll 1$. Here we give a more complete elaboration of this model.

Due to the large beam ion mass $m_b \gg m_e$, where m_e is the electron mass, and for beams that are much longer than the resonant wavelength of the beam-plasma two-stream instability $l_b \gg v_b/\omega_{pe}$, where l_b is the beam length and $\omega_{pe}=(4\pi e^2n_p/m_e)^{1/2}$ is the electron plasma frequency, the result of the instability is to produce short-wavelength electrostatic wave perturbations with frequency close to the plasma frequency $\omega \approx \omega_{pe}$. The unstable waves have a phase velocity which is close to the beam velocity, $\omega/k_z \approx \omega_p/k_z \approx v_b$. In what follows we assume that the beam transverse dimensions have a

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single characteristic length of order of the beam radius r_b which is not much smaller than electron collisionless skin-depth, $r_b \gtrsim c/\omega_{pe}$. In this case $k_z r_b \gg 1$ and the instability is purely longitudinal. The radial dependence appears in all equations as a variable.

The unstable wave growth saturates either by longitudinal trapping of plasma electrons in the wave, which happens when the electron's amplitude of velocity oscillation in the wave become of order of the phase velocity of the wave $v_m^e \sim \omega/k_z \sim v_b$, or by trapping of beam ions, which happens when the beam ion's amplitude of velocity oscillation in the wave becomes of order of the difference between the beam velocity and the phase velocity of the wave $v_m^b \sim v_b - \omega/k_z \sim \gamma/k_z \approx (\gamma/\omega_{pe})v_b$. Here we used the fact that $\omega - k_z v_b \sim \gamma$, where $\gamma = \mathrm{Im}\,\omega \sim \omega_{pe}(\omega_{pb}/\omega_{pe})^{2/3}$ is the linear growth rate of the instability, and $\omega_{pb} = (4\pi Z_b^2 e^2 n_b/m_b)^{1/2}$ is the plasma frequency of the beam ions [9]. Because the electrons and beam ions both experience the same wave electric field, their oscillation velocities are related by $m_e \omega v_m^e = m_b(\omega - k_z v_b)v_m^b/Z_b$, or equivalently, $v_m^e \sim (m_b/Z_b m_e)(\gamma/\omega_{pe})v_m^b$. Therefore, if the beam ions become trapped by the wave before the electrons, $v_m^b \sim (\gamma/\omega_{pe})v_b$ and the corresponding amplitude of the electron velocity oscillations has to satisfy the relation $v_m^e \sim (m_b/Z_b m_e)(\gamma/\omega_{pe})^2 v_b \lesssim v_b$, or $[Z_b(m_b/m_e)(n_b/n_p)^2]^{1/3} \lesssim 1$. Otherwise, if $[Z_b(m_b/m_e)(n_b/n_p)^2]^{1/3} \gtrsim 1$, the electron velocity oscillation amplitude becomes $v_m^e \sim v_b$ first, and the saturation is determined by electron trapping. If the saturation is caused by beam ion trapping, the beam density becomes highly modulated in the longitudinal direction. The beam splits longitudinally into short bunches with length $\sim v_b/\omega_{pe} \ll l_b$.

The electric field of the waves also generates average transverse forces on the beam ions. An average ambipolar electric field is set up which acts against the Lorentz force and ponderomotive pressure of the wave exerted on the cold plasma electrons according to

$$e\langle E_x\rangle \sim e\frac{\langle v_z^e\rangle}{c}\langle B_y\rangle + m_e\frac{(v_m^e)^2}{4r_b}, \tag{1}$$

where r_b is the beam radius. At the same time, the wave electric field produces an average nonlinear electron longitudinal current density $\langle j_z^{non}\rangle = -e\langle \delta n^e \delta v_z^e\rangle \approx -en_p\langle(\delta v_z^e)^2\rangle/v_b \approx -en_p(v_m^e)^2/2v_b$ in addition to the beam current density j_z^b. Here we used the linear relation $\delta n^e \approx n_p(k_z/\omega)\delta v_z^e \approx n_p \delta v_z^e/v_b$. The total injected current density $j_z^b + \langle j_z^{non}\rangle$ will produce an inductive plasma response current density $\langle j_z^{ind}\rangle = -en_p\langle v_z^e\rangle$, which will reduce the total injected current density by the factor $1/(1+r_b^2/\lambda_{pe}^2)$, where $\lambda_{pe} = c/\omega_{pe}$ is the collisionless skin-depth. Therefore the total current density in the plasma becomes

$$\langle j_z\rangle \approx \frac{j_z^b}{(1+r_b^2/\lambda_{pe}^2)}\left[1 - \frac{1}{2}\frac{n_p}{Z_b n_b}\left(\frac{v_m^e}{v_b}\right)^2\right], \tag{2}$$

and the associated azimuthal self-magnetic field is

$$\langle B_y\rangle \sim \frac{2\pi}{c}\langle j_z\rangle r_b \sim \frac{2\pi Z_b e n_b r_b \beta_b}{(1+r_b^2/\lambda_{pe}^2)}\left[1 - \frac{1}{2}\frac{n_p}{Z_b n_b}\left(\frac{v_m^e}{v_b}\right)^2\right]. \tag{3}$$

Note from Eqs. (2) and (3) that the presence of waves in the plasma due to the instability can cause the reversal of the total longitudinal current density and associated azimuthal self-magnetic field if $(v_m^e/v_b)^2 > (2Z_b n_b/n_p)$. The average electron flow produced by the inductive electric field ($\langle v_z^e\rangle \to 0$ as $c \to \infty$) is given by

$$\langle v_z^e\rangle \simeq \frac{Z_b n_b}{n_p}\frac{v_b}{(1+\lambda_{pe}^2/r_b^2)}\left[1 - \frac{1}{2}\frac{n_p}{Z_b n_b}\left(\frac{v_m^e}{v_b}\right)^2\right]. \tag{4}$$

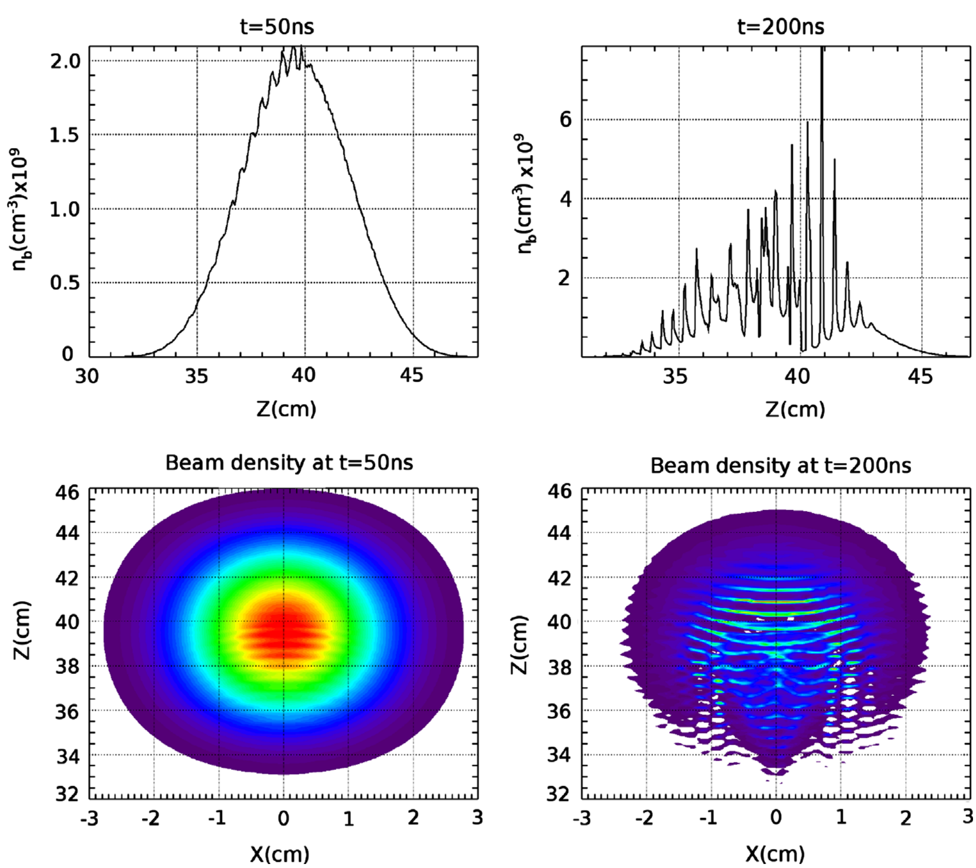

Fig. 1. Plots of ion beam density; beam density profile along $n_b(x=0,z,t)$ plotted versus z at $t=50$ ns and $t=200$ ns (top); beam density (x,z) contour plots at $t=50$ ns and $t=200$ ns (bottom).