analysis, one must exercise the utmost care in attempting to draw conclusions about electronic structure from Raman excitation profile data.

We thank A. Nitzan for numerous enlightening discussions.

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Propagation and Defocusing of Intense Ion Beams in a Background Plasma*

R. N. Sudan
Laboratory of Plasma Studies, Cornell University, Ithaca, New York 14853
(Received 4 October 1976)

The effect of collective interactions between an intense ion beam and a background plasma is found to increase the plasma return current above that necessary for current neutralization, which eventually contributes to defocusing of the beam.

Proposals for replacing high-powered lasers or electron beams in inertial confinement schemes for controlled fusion by intense proton beams[1,2] (~10 MeV) and high-energy (10^2 GeV) heavy ions[3,4] have appeared recently. A critical problem in these proposals is the propagation of the beam from the injector to the target (~10 m distance) in an ambient low-density plasma produced by the previous explosions. In this Letter, we examine the process of current neutralization by the plasma during injection and, in particular, the effect of collective electrostatic interactions on the development of the plasma current. The significance of the magnetic kink mode on such propagation has been examined in an earlier calculation.[5]

It is well known that when a high-powered relativistic electron beam is injected into a plasma, a return current is induced within the beam cross section if the beam radius a exceeds c/ω_e, where ω_e is the electron plasma frequency.[6] This current neutralizes the self-magnetic field of the beam, but it decays after a time $\tau_d \simeq \pi\sigma a^2/c^2$, the magnetic diffusion time, where σ is the plasma conductivity.[7] Plasma currents are also induced when an intense ion beam is injected into a plasma but we show below that, in this case, collective interaction between the beam ions and the background plasma leads to a frictional force which accelerates the plasma electrons. Because of the large momentum of the ion beam, this effect could lead to a return plasma current which actually exceeds the beam current. The resulting reversed magnetic field associated with the net current leads to beam defocusing. The magnitude of this effect is computed below.

Let a well-collimated beam of ions mass m_b, charge $Z_b e$, density n_b, and radius a be injected with velocity w_b into a plasma of electron density n_e, temperature T_e with ion charge Ze. We shall assume that $Zn_e \gg Z_b n_b$ and beam temperature $T_b \ll m_b w_b^2$. The quasilinear equation[8] for the average electron distribution is

$$\frac{\partial}{\partial t}\langle f\rangle - \frac{e}{m_e}E_z\frac{\partial}{\partial v}\langle f\rangle = \frac{\partial}{\partial v}\left(D\frac{\partial}{\partial v}\langle f\rangle\right) + C, \qquad (1)$$

where

$$E_z(r) = \frac{4\pi}{c^2}\frac{\partial}{\partial t}\int_0^r\frac{dr'}{r'}\int_0^{r'}dr''\ r''\ J_t \equiv \left(\frac{4\pi}{c^2}\right)\nabla^{-2}\frac{\partial J_t}{\partial t}$$

is the induced electric field, $J_t = J_e + J_b$ is the sum of the electron and beam current densities, C is a collision operator, and D is the quasilinear diffusion coefficient[8] resulting from the two-stream instability between the beam ions and the plasma electrons, with

$$D = \frac{e^2}{m_e^2}\sum_k \frac{|E_k|^2\gamma_k}{(\omega_k - kv)^2 + \gamma_k^2}.$$

On taking the velocity moment of (1), we obtain for the electron current J_e,

$$\left[\left(1 - \frac{\nabla^{-2}}{\lambda^2}\right)\frac{\partial}{\partial t} + \frac{1}{\tau_{ie}}\right]J_e = \frac{\nabla^{-2}}{\lambda^2}\frac{\partial J_b}{\partial t} - \frac{e}{m_e}\sum_k \frac{\omega_e^2\gamma_k}{(\omega_k - kw_e)^3}\frac{k|E_k|^2}{4\pi}, \qquad (2)$$

where $\lambda = c/\omega_e$ and $J_e = -n_e e w_e$. In deriving (2) we have assumed that (i) the quasilinear term for momentum exchange with the waves is computed for nonresonant particles, i.e., $\omega_k \gg kv$ since $\omega_k/k \sim w_b \gg w_e$, $\gamma_k \ll \omega_k$, and (ii) the collision time is approximated by the electron plasma ion collision time τ_{ei}.

Immediately after the beam is injected and before the unstable waves have a chance to grow we may neglect the collisional and wave terms. This leads to the conventional result that for $\nabla^{-1} \sim a \gg \lambda$, $J_e + J_b \simeq 0$, (i.e., complete current neutralization and, therefore, magnetic neutralization). For $t > \tau_r$ the beam rise time and $a \gg \lambda$, we have $\partial J_e/\partial t = (\lambda^2/\tau_{ie})\nabla^2 J_e$, and in the absence of instabilities the characteristic time for current decay is $\tau_d = \frac{1}{4}\tau_{ei}a^2/\lambda^2 = \pi\sigma a^2/c^2$. However, in the presence of instabilities and for $\tau_d \gg t > \tau_r$ and $\gamma_k t > 1$, $\omega_k \simeq \omega_e \gg kw_e$, and J_e approaches[9] a limiting value given by

$$\left(1 - \frac{\nabla^{-2}}{\lambda^2}\right)J_e = \left(\frac{\nabla^{-2}}{\lambda^2}\right)J_b - \left(\frac{e}{m_e}\right)\sum_k \frac{k|E_k|^2}{8\pi\omega_k}, \qquad (3)$$

where we have recognized that $\partial|E_k|^2/\partial t = 2\gamma_k|E_k|^2$. An estimate of the saturation level of $\sum_k|E_k|^2$ can be made by equating the wave energy density to the energy recovered from the slowing down of the beam ions to the phase velocity ω_k/k; thus,[9]

$$2\textstyle\sum_k |E_k|^2/8\pi \simeq n_b m_b w_b\,\delta w_b, \qquad (4)$$

where $\delta w_b \simeq 0.58\gamma_k/k = 0.5w_b(n_b/2n_e)^{1/3}(Z_b m_e/m_b)^{1/3}$. Substituting (4) in (3), we obtain

$$(1 - \nabla^{-2}/\lambda^2)J_e = [-0.25(n_b/2n_e)^{1/3}(m_b/Z_b m_e)^{2/3} + \nabla^{-2}/\lambda^2]J_b. \qquad (5)$$

Thus for $\nabla^{-2}/\lambda^2 \gg 1$, the net plasma current is given by

$$J_t = J_e + J_b = 0.25(n_b/2n_e)^{1/3}(m_b/Z_b m_e)^{2/3}\lambda^2\nabla^2 J_b. \qquad (6)$$

If the beam current density profile is expressed as $J_b = (I_b/\pi a^2)\exp(-r^2/a^2)$, then for $n_b/2n_e \sim 10^{-3}$, $m_b/Z_b m_e \sim 3\times10^4$, $a/\lambda \sim 5$, $J_t = 3.8(I_b/\pi a^2)(1 - r^2/a^2)\exp(-r^2/a^2)$. Thus, an ion beam can be overneutralized by the plasma current.

As the electron distribution shows acceleration under the action of the field E_z induced by beam injection, there exists the possibility of two-stream interaction between the electrons and plasma ions. This interaction by the spectrum II (see Fig. 1) acts as a brake on the acceleration process. If the beam rise time τ_r is so short that $\gamma_s\tau_r \lesssim 1$, where $\gamma_s \sim (m_e/m_i)^{1/2}\,\omega_e/\sqrt{8\pi}\,k^2\lambda_d^2$ is the ion sound growth due to electron drift w_e, then the braking force is negligible during this time interval. However, when $w_e > (T_e/m_e)^{1/2}$ the interaction becomes strong and the Buneman instability determines the growth rate. In this case Eq. (3) is modified to

$$\left(1 - \frac{\nabla^{-2}}{\lambda^2}\right)J_e - \left(\frac{\nabla^{-2}}{\lambda^2}\right)J_b = -\frac{e}{m_e}\left\{\sum_k^{\mathrm{I}}\frac{k|E_k^{\mathrm{I}}|^2}{8\pi\omega_k} - \sum_k^{\mathrm{II}}\frac{|E_k^{\mathrm{II}}|^2}{8\pi w_e}\right\}, \qquad (7)$$

where $|E_k^{\mathrm{I}}|^2$ and $|E_k^{\mathrm{II}}|^2$ are the final saturated levels. Estimating $|E_k^{\mathrm{II}}|^2/8\pi \simeq \frac{1}{8}n_e m_e w_e^2$ from the limit imposed by plasma ion trapping by spectrum II, we obtain, as before,

$$(1 - \tfrac{1}{8}\lambda^2\nabla^2)J_e = \left[-1 + 0.25\left(\frac{n_e}{2n_e}\right)^{1/3}\left(\frac{m_b}{Zm_e}\right)^{2/3}\lambda^2\nabla^2\right]J_b. \qquad (8)$$

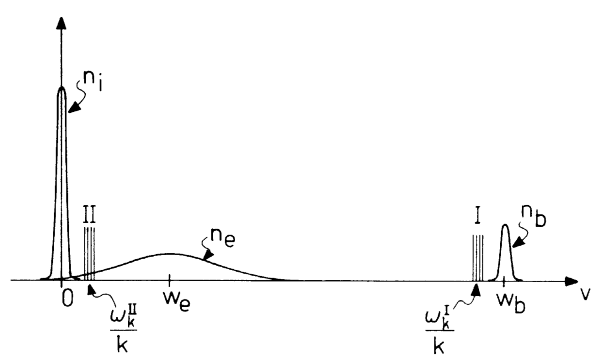

FIG. 1. Schematic of plasma electron, ion, and beam ion distributions and phase velocity of unstable wave spectra.

Since $\lambda^2\nabla^2 \ll 1$, Eq. (8) actually reduces to Eq. (5). Now the plasma electrons are also being heated by collective interactions.[10] An estimate of this temperature rise can be obtained by taking a second velocity moment of Eq. (1). If this temperature rise is such that $w_e < (T_e/m_e)^{1/2}$, then the rate of growth of spectrum II is diminished to that appropriate for the ion sound instability and the braking terms to be included in Eq. (2) are given approximately by

$$-\left(\frac{\pi}{8}\right)^{1/2}\sum_k \frac{|E_k^{\mathrm{II}}|^2}{k\lambda_D^2 v_e}\left(w_e - \frac{\omega_k}{k}\right)\exp\left[\frac{-m_e}{2T_e}\left(\frac{\omega_k}{k} - \omega_e\right)^2\right],$$

where λ_D is the Debye length. This is much smaller than the case for Buneman instability considered above, in which case Eq. (5) is even more valid.

In conclusion, we note that the unequal frictional forces resulting from collective interaction between the electrons and the beam and plasma ions leads to excess plasma current over that required for current neutralization. The reversal of the self-magnetic field by this effect could lead to defocusing of the beam.

An estimate of the defocusing of beam is obtained from the radial momentum balance

$$N_b m_b d^2a/dt^2 = (2\pi/c)\int_0^a dr\, rJ_b B_\theta, \qquad (9)$$

where N_b is the number of beam ions per unit length. Taking Eq. (5) into account, we obtain for a Gaussian radial profile,

$$d^2a/dt^2 = \alpha\nu w_b^2(\lambda^2/a_0^2)e^{-2}g/a \equiv G/a, \qquad (10)$$

where $\nu \equiv N_b Z_b^2 e^2/m_b c^2$, $\alpha \equiv 0.25(n_b/2n_e)^{1/3}(m_b/Z_b m_e)^{2/3}$, $g \equiv |1 - \int_0^a dr\, J_b^2/aJ_b^2(a)|$, $a_0 = a(t=0)$. We have assumed plasma ions immobile and charge neutrality during the expansion phase, i.e., $n_e a^2$ is constant. The solution of Eq. (10) is given by

$$t = (a_0^2/2G)^{1/2}\int_0^{[\ln(a/a_0)]^{1/2}} dy\, \exp(y^2). \qquad (11)$$

Thus, the time taken to expand to $a/a_0 \sim 2-3$ should be longer than the pulse transit time to the target for the defocusing effect to be small.

The characteristic defocusing time is thus given by $t_0 = a_0/(2G)^{1/2}$ which can be written as

$$t_0 = 10.9g^{-1/2}(N_b Z_b/\pi n_e a_0^2)^{-2/3}(2m_b/m_e)^{1/6}(a_0/w).$$

Consider 25-BeV, U^{+3} ions for which $I_b = 10^4$ A, $W_b = 1.3\times10^{10}$ cm/sec, $Z_b = 3$, and $a_0 = 2.5$ mm in a background plasma of density $n_e = 10^{14}$ cm^{-3}. For these conditions with $g \sim 1$, we obtain $t_0 = 5\times10^{-9}$ sec, which is comparable to the beam pulse time. In conclusion, this self-defocusing feature provides a limitation on the parameters available for beam propagation in the target chamber. A high plasma density is obviously a favorable condition but it may lead to beam stripping and therefore a higher effective Z_b.

I am grateful to Dr. Harold Furth for pointing out that a similar effect is predicted in the collisional regime,[11,12] and to Dr. Marshall Rosenbluth for pointing out the defocusing aspect of overneutralization.

*Work supported by the U. S. Energy Research and Development Administration.

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