Intense charged particle beam propagation into vacuum*

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ABSTRACT

The propagation of intense charged particle beams into vacuum without the aid of externally applied confining magnetic fields is under investigation both theoretically and experimentally. In the configuration under study an intense relativistic electron beam is injected through a localized plasma source into vacuum. Ions drawn into the vacuum region by the electron beam space charge provide the required neutralization for the effective propagation of beam electrons over significant distances. Experimental measurements indicate that under optimum conditions, both the ion and electron components of the propagating electron/ion beam are well focused radially. An equilibrium for this propagating electron/ion beam in which both species are in radial force balance has been postulated and matched to both electron and ion beam parameters at the source. Studies of the propagation of such an electron/ion beam across a transverse magnetic field are also reported.

1. INTRODUCTION

Studies of the propagation of intense charged particle beams into vacuum have been underway at the University of Maryland since 1984. The primary goal of this research program is to determine under what conditions charged particle beam energy may be propagated into vacuum without the aid of externally confining magnetic fields or conducting boundaries. Toward this goal we have undertaken experimental and theoretical studies of the injection of an intense, relativistic electron beam through a localized plasma into vacuum.[1-5] Typically the injected electron beam current is several times larger than a related space charge limiting value, given approximately by[6]

$$I_e = \frac{4\pi\varepsilon_o m_o c^3}{e} \frac{(\gamma^{2/3} - 1)^{3/2}}{[1 + 2\ell n(r_w/r_b)][1-f]} \quad (1)$$

Here m_o is the electron rest mass, e the electronic charge, c the velocity of light in vacuum, r_w is the conducting drift tube radius, ε_o is the permittivity of free space, r_b is the electron beam radius, and $\gamma = [1 - \beta^2]^{-1/2}$ is the relativistic mass factor for the electrons at injection where $\beta = v/c$. $f = n_i/n_e$ represents any neutralization of the electron beam space charge provided by positive ions. Upon injection at these high current levels, a virtual cathode is formed at the injection point and ions are accelerated downstream by the strong electric fields associated with the virtual cathode. These accelerated ions then form an ion channel that can provide the neutralization necessary for effective propagation of those electrons generated later in the pulse. Under optimum experimental conditions, excellent radial confinement of the propagating beam electrons in the absence of any external confining magnetic fields can be observed. Such propagation has been observed in conducting drift tubes of various diameters and, recently, in large-diameter non-conducting drift tubes as well.[5]

Although effective electron beam propagation by this mechanism was observed at several laboratories over the last decade,[1,2,7,8] only recently was it determined that the accelerated ion beam propagates in excellent radial force balance as well.[3] As a result of these observations, an equilibrium has been postulated for the propagating electron/ion beam in which both species are in radial force balance in the absence of confining magnetic fields.[9,10] In this equilibrium, the ion beam is confined by the electron space charge and the electron beam is confined by balancing the radially focusing force due to the beam

*This work supported by DOE and AFOSR.

self-magnetic field and the radially defocusing forces due to space-charge forces and a $\vec{\nabla}P$ force resulting from finite electron temperature and the electron radial density distribution.

In this paper, a theoretical discussion of the equilibrium of such a propagating electron/ion beam is presented in section 2. Experimental studies of propagation in such systems are presented in section 3., including recently obtained measurements of the propagation of such beams across transverse applied magnetic fields. Conclusions are drawn in section 4.

2. THEORETICAL DISCUSSION

A schematic of our system is shown in Figure 1. An electron beam is injected with voltage V_o and current I_o into a long drift tube of radius r_w. In order to have electron beam propagation, ions are provided by a region immediately downstream of the injection surface. The properties of this localized source region are the rate S_i (C/sec) at which ions are formed and the potential V_{io} at which the ions are created. The ions and beam electrons are then able to propagate downstream with the ions initially at rest gaining kinetic energy as they fall through the potential difference $V_{io} - V$, and the beam electrons losing kinetic energy due to the downstream potential depression V. The localized region can be formed by electron beam ionization of a neutral gas cloud[4] or preformed by laser irradiation of a target. The combination of the injected electron beam and localized source is able to create the large localized space charge fields for the ions to gain the needed energy for beam propagation downstream. The downstream electron-ion beam is assumed to have a mean axial electron velocity $V_{ze} = \beta_{ze}c$ and a mean axial ion velocity $V_{zi} = \beta_{zi}c$. Each species has a temperature, T_e and T_i, and we assume that, in general, there is no charge neutrality and/or current neutrality, thus resulting in a self-electric field E_{sr} and self-magnetic field $B_{s\phi}$. The goal of this model is to interrelate all the system parameters.

The analysis of the proposed downstream equilibrium for the electron/ion beam can be described as follows. It is assumed that the particle distribution function for each component (electron and ion) of the beam is an isotropic relativistic Maxwellian in the frame travelling at the mean velocity associated with that component. The downstream force balance equation for each species in the laboratory frame is then given by

$$q_j n_j(r)[E_{sr}(r) - V_{zj}B_{s\phi}(r)] - kT_j \frac{dn_j(r)}{dr} = 0 \tag{2}$$

where the electric and magnetic self fields are given by

$$E_{sr}(r) = \frac{e}{\varepsilon_o r} \int_o^r [Zn_i(r') - n_e(r')]r'dr' \tag{3}$$

and

$$B_{s\phi}(r) = \frac{\mu_o e}{r} \int_o^r [Zn_i(r')V_{zi} - n_e(r')V_{ze}]r'dr', \tag{4}$$

and T_j is the electron or ion temperature in the laboratory frame. Assuming Z = 1, the solution of these equations is

$$n_e(r) = \frac{n_{eo}}{[1+(r/a)^2]^2} = \frac{n_{eo}}{n_{io}} n_i(r), \tag{5}$$

where

$$n_{eo} = \frac{8\varepsilon_o}{e^2a^2} \frac{kT_e(1-\beta_{zi}^2) + kT_i(1-\beta_{ze}\beta_{zi})}{(\beta_{ze} - \beta_{zi})^2} \tag{6}$$

and

$$n_{io} = \frac{8\varepsilon_o}{e^2a^2} \frac{kT_e(1 - \beta_{ze}\beta_{zi}) + kT_i(1 - \beta_{ze}^2)}{(\beta_{ze} - \beta_{zi})^2} \tag{7}$$

are the familiar Bennett pinch density profiles where "a" is the effective beam radius for each species. In contrast to the usual derivations of the Bennett equilibrium,[11-13] this result has been obtained without requiring that the particle axial velocity is much greater than any transverse velocity.

In order to connect this downstream equilibrium with the electron and ion beam parameters at the injection point, we apply the continuity of current for electrons

$$I_o = \frac{8\pi\varepsilon_o c\beta_{ze}}{(\beta_{ze} - \beta_{zi})^2}\left[\frac{kT_e}{e}(1 - \beta_{zi}^2) + \frac{kT_i}{e}(1 - \beta_{ze}\beta_{zi})\right]\left[\frac{(r_w/a)^2}{1 + (r_w/a)^2}\right] \qquad (8)$$

and for ions

$$S_i = \frac{8\pi\varepsilon_o c\beta_{zi}}{(\beta_{ze} - \beta_{zi})^2}\left[\frac{kT_e}{e}(1 - \beta_{ze}\beta_{zi}) + \frac{kT_i}{e}(1 - \beta_{ze}^2)\right]\left[\frac{(r_w/a)^2}{1 + (r_w/a)^2}\right]. \qquad (9)$$

In addition, we apply conservation of single particle energy, which for electrons gives

$$1 + \frac{eV_o}{m_e c^2} + \frac{eV}{m_e c^2} = \bar{\gamma}_e \frac{K_3(\alpha_e)}{K_2(\alpha_e)} - \frac{kT_e}{m_e c^2}, \qquad (10)$$

and for ions

$$1 + \frac{eV_{io}}{m_i c^2} - \frac{eV}{m_i c^2} = \bar{\gamma}_i \frac{K_3(\alpha_i)}{K_2(\alpha_i)} - \frac{kT_i}{m_i c^2}. \qquad (11)$$

Here V is the downstream potential on axis, K_3 and K_2 are modified Bessel functions, $\bar{\gamma}_j = (1 - \beta_{zj}^2)^{-1/2}$, and $\alpha_j = m_j c^2/\bar{\gamma}_j kT_j$. The terms on the right-hand side of Equations (10) and (11) represent the average downstream value of gamma.

Assuming that I_o, V_o, r_w/a, T_e, and T_i are known, β_{ze}, β_{zi}, S_i, and V_{io} can be found from the above equations. In addition, the net current in the propagating electron/ion beam can be found from

$$I_{net} = \frac{8\pi\varepsilon_o c}{(\beta_{zi} - \beta_{ze})}\left[\frac{kT_e}{e} + \frac{kT_i}{e}\right]\left[\frac{(r_w/a)^2}{1 + (r_w/a)^2}\right] \qquad (12)$$

and the fractional charge neutralization can be found from

$$f = \frac{n_i}{n_e} = \frac{(1 - \beta_{ze}^2)T_i + (1 - \beta_{ze}\beta_{zi})T_e}{(1 - \beta_{ze}\beta_{zi})T_i + (1 - \beta_{zi}^2)T_e}. \qquad (13)$$

A typical set of results obtained from our model are displayed in Figures 2 and 3. To obtain these results we solve Equations (8) - (11) by choosing V_o, I_o, r_w/a, T_e, and T_i, and then determine β_{ze}, β_{zi}, S_i, and V_{io}. The more relevant quantities from the analysis for comparison with experiments are the net current, Equation (12), and the fractional charge neutralization, Equation (13). These latter quantities are plotted in Figures 2 and 3.

In Figure 2, we have $V_o = 1$ MV, $r_w/a = 10$, and $T_i = 0$ and have plotted I_{net} and f versus T_e with I_o a parameter. A main feature of these results is seen in Figure 2a at the point where $I_{net} = I_o$, i.e., the net current propagated downstream is the injected electron current. At this "critical" temperature, $T_e = T_e^*$, where $\beta_{zi} = 0$, the system is charge neutral but not current neutral, (see Figure 2b). Specifically if $I_o = 5$ kA, $T_e^* \simeq 60$ kev, and if $I_o = 30$ kA, then $T_e^* \simeq 250$ kev. This temperature represents the traditional Bennett state. Acceptable equilibria exist for our experimental system for temperatures $T_e < T_e^*$.

We find that temperatures just below T_e^* provide system parameters, S_1 and V_{1o}, very close to the calculated values for ion-ion avalanche ionization in the localized gas cloud.

In Figure 3, we display the effects of finite ion temperature. We have plotted I_{net} and f versus T_e with T_i as a parameter. The other fixed system parameters are V_o = 1 MV, I_o = 20 kA, and r_w/a = 10. The effects of finite ion temperature are to lower the value of the critical temperature T_e^* and in turn eliminate the existence of a charge neutral state. That is, the state of no current neutralization (zero ion velocity) still occurs at T_e^*, but this state requires a net negative charge.

We have found self-consistent downstream equilibria between electrons and ions with no applied axial magnetic field. The electrons are confined by the self-magnetic field and the ions by the self-electric field. In addition, the model calculates the required localized ion source properties necessary to achieve the equilibrium. The system is self-consistently derived from a relativistic Maxwellian particle distribution for each species.

3. EXPERIMENTAL RESULTS

The experimental configuration used for most of the propagation experiments is shown in Figure 4. An intense, relativistic electron beam (1 MeV, 30 kA, 30 ns) is emitted from a 4mm diameter tungsten cathode and accelerated toward a stainless steel anode. A 12 mm diameter aperture in the anode plate allows most of the beam electrons to pass through the anode plane into the 15 cm diameter conducting downstream drift tube. Ions are produced by electron impact ionization (and later ion-ion avalanche ionization) of a localized hydrogen gas cloud produced by a fast puff valve. The timing of the puff valve firing is carefully synchronized with the timing of the electron beam injection such that the gas cloud is confined to within 2 cm of the downstream side of the anode plane at the time of beam injection.

Beam propagation is observed using a variety of small-area current collectors installed both on the drift tube wall and as a radial array that can be inserted into the drift tube from the downstream end. Total beam current and energy reaching the downstream end of the drift tube can be measured using a 7.4 cm diameter combination Faraday cup/calorimeter.

Results of measurements of the radial distribution of beam current at z=54 cm downstream of the anode are shown in Figure 5. It is clear from these results that good radial confinement of the beam electrons is only achieved for peak localized gas cloud pressures of about 35 mtorr. At this optimum value, however, currents substantially above the space charge limiting value (about 4 kA) can be propagated to a distance 70 cm downstream of the anode, as shown in Figure 6. At this point, net propagated beam current falls rapidly to a value comparable to that achievable without any ion source present at all. Previous measurements have determined that this effect is directly attributable to the limited electron beam injection pulse duration. Because time is consumed in accelerating the ions downstream to form the neutralizing ion channel, at some point the injection pulse terminates before the ions can propagate further downstream. In addition to these measurements of the radial distribution of the propagated beam current, radiographs of targets activated by the accelerated protons that provide the downstream neutralizing ion channel indicate that the radial confinement of the ion component of the beam is comparable to that of the electrons under optimum conditions.[4] This propagation mechanism has been observed in conducting drift tubes of radius 7.5 and 30 cm,[1,2,4] and in a nonconducting drift tube of radius 15 cm.[5]

Recently, we have begun to investigate the propagation of such co-moving electron/ion beams across transverse applied magnetic fields. The basic experimental configuration used for these studies is shown in Figure 7. A transverse magnetic field is produced by a Helmholtz coil mounted outside the drift tube in the manner shown. Transverse magnetic field distributions in both the axial and radial directions are shown in Figure 8.

In order to determine the extent to which the co-moving electron/ion beam can propagate across a transverse magnetic field more readily that single electrons alone, a control experiment was performed in which electron beam current was injected in the usual manner but the ion source was removed. A downstream collimator was installed before the transverse magnetic field to simulate the radial current distribution of the propagating electron/ion beam at that point under optimum conditions. The current reaching the end of the drift tube was then measured as a function of transverse magnetic field amplitude using the Faraday cup. These results, shown in Figure 9, indicate that a transverse field of about 75 gauss was necessary to reduce the current measured by the Faraday cup to 1/2 of the value observed with no transverse field present. This transverse field amplitude is consistent with that required if the electron motion through the transverse field region and subsequent drift region to the Faraday cup is in accord with single particle theory.

When the collimator is removed and the localized ion source is provided optimally, approximately four times more transverse field amplitude (300 Gauss) is required to reduce the propagated beam current to 50% of the value observed without the tranverse field, as shown in Figure 9. It is interesting to note that the value of the beam self magnetic field at the edge of the beam predicted by theory is approximately

$$B_{s\phi} \cong 200 \, \frac{I_e[kA]}{a[cm]} \tag{14}$$

Thus, for a beam of 3 cm radius carrying a current of 10 kA, a transverse field of about 650 gauss would be sufficient to completely cancel the beam self field on one side of the beam. Further experiments are required to definitively determine the mechanism that leads to beam loss as the transverse field is raised, but the possibility that the transverse magnetic field simply destroys the beam equilibrium described in section 2. cannot be overlooked.

4. CONCLUSIONS

Both experimental and theoretical studies of the propagation of intense, relativistic electron beams in vacuum after passage through a localized ion source indicate that effective propagation can occur with both electrons and accelerated ions in radial force balance. The effective propagation velocity, however, is limited by the accelerated ion velocity. As a result, unless injection configurations can be found in which the electron and ion velocities are more nearly equal, significant electron beam energy will be lost at the beam front throughout the propagation process. The propagating electron/ion beam does, however, appear to be able to propagate across significantly stronger transverse magnetic fields that can an equivalent unneutralized electron beam.

Further studies of this propagation process are underway to investigate this process when the injection pulse duration is considerably longer, about 100 ns. In this manner, the effects of instabilities or ion source depletion on the propagation process should be more readily apparent.

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