Propagation in Vacuum of an Intense Electron Beam Injected Through a Localized Plasma

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Propagation of an intense relativistic electron beam (1 MeV, 27 kA, 30 ns) in vacuum after passage through a localized hydrogen plasma of ~ 2-cm width has been observed. A large fraction of the injected current was found to propagate in a vacuum drift tube to a distance in excess of 50 cm downstream of the plasma. A description of the process is proposed which links the electron beam propagation with collective ion acceleration and which relates to cosmic-ray acceleration and laser experiments.

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The generation and propagation of intense relativistic electron beams (IREB) have been the subject of many theoretical and experimental studies, and the work prior to 1982 is reviewed in the book by Miller.[1] With respect to beam propagation, one distinguishes between propagation in (a) vacuum, (b) plasma, and (c) neutral gas, and the beam current I is generally related to the space-charge–limiting current I_L in (a), and the Alfvén-Lawson current[2,3] I_A in (b) and (c). Thus, in a vacuum drift tube and in the absence of charge-neutralizing ions, IREB propagation is possible only if $I < I_L$ and if a focusing magnetic field B is present. The space-charge–limiting current then depends on whether both the cathode and the drift tube or only the drift tube are immersed in the magnetic field.[4] In the first case, the assumption that $B \to \infty$ yields the formula for I_L by Bogdankevich and Rukhadze.[5]

For a beam in vacuum with accelerated ions, as in our experiments, neither I_L nor I_A can be applied. In this general case, the propagation is limited by the amount of the fractional charge and current neutralization, f_e and f_m, respectively, and by power-balance considerations, i.e., by the fact that kinetic energy is spent to build up electromagnetic field energy along the path of propagation.[6] The beam particle current can substantially exceed both I_A and I_L as $f_e \to 1$ and $f_m \to 1$, and propagation into free-space vacuum is possible if comoving particles of opposite charge are present to assure both charge and current neutralization ($f_e = 1$, $f_m = 1$).

In our present paper, we describe experiments in which IREB propagation in a vacuum drift tube is achieved with currents $I >> I_L$ when a source of positive ions is provided at the drift tube entrance. These studies were motivated by observations in collective ion acceleration experiments at our laboratory.[7,8] The emphasis in our previous studies with vacuum drift tubes, as well as in related work by other groups,[9–11] was on detection and measurement of the collective acceleration of ions to high energies. Gilad and Zinamon,[10] for example, accelerated ions from an anode foil with an IREB and observed beam propagation with a $\dot{B}$ loop. A new feature in our experiments is that the source of ions is a well-localized gas cloud at the anode and that the pressure in the cloud can be controlled externally. The observations that the electron beam propagation distance depends critically on the gas density and that the pulse width (rather than peak electron current) decreases with distance are new results of our recent studies which are reported below.

The experimental configuration used for the studies is shown in Fig. 1. An IREB [1 MeV, 27 kA, 30 ns full width at half maximum (FWHM)] from a 3-mm-diam tungsten cathode was injected through a 26-mm hole in the stainless-steel anode plate (located 6.3 mm from the cathode) into the drift tube region. The drift tube diameter was 15 cm, and the vacuum pressure was in the range 10^{-5}–10^{-4} Torr. No focusing magnetic field was used. A well-localized hydrogen gas cloud was pro-

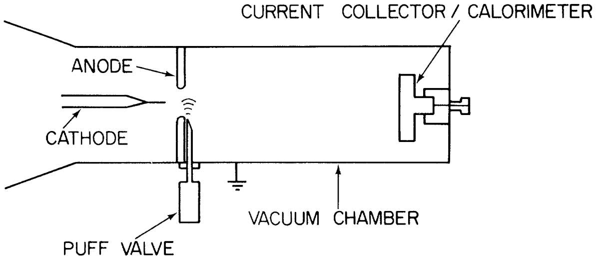

FIG. 1. Experimental configuration for the beam propagation studies with the puff-valve ion source at the anode.

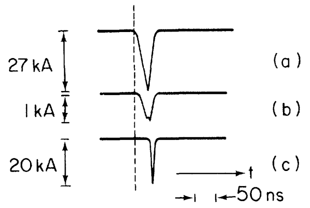

FIG. 2. Current-collector wave forms for (a) injected current, (b) current at $z = 38$ cm with no gas injected, and (c) current at $z = 38$ cm with optimized gas-cloud pressure at injection.

duced on the downstream side of the anode by firing a fast gas puff valve 540 μs before electron beam injection. Measurements using a fast ionization gauge showed that the effective axial extent of the cloud is less than 2 cm (FWHM) at the time of beam injection, independent of the peak pressure of the gas cloud. By varying the charging voltage of the capacitor bank that powers the puff valve, the effective pressure in the cloud seen by the electron beam could be varied up to a peak pressure of about 100 mTorr. Ionization of the gas results from electron-impact and ion-avalanche processes.

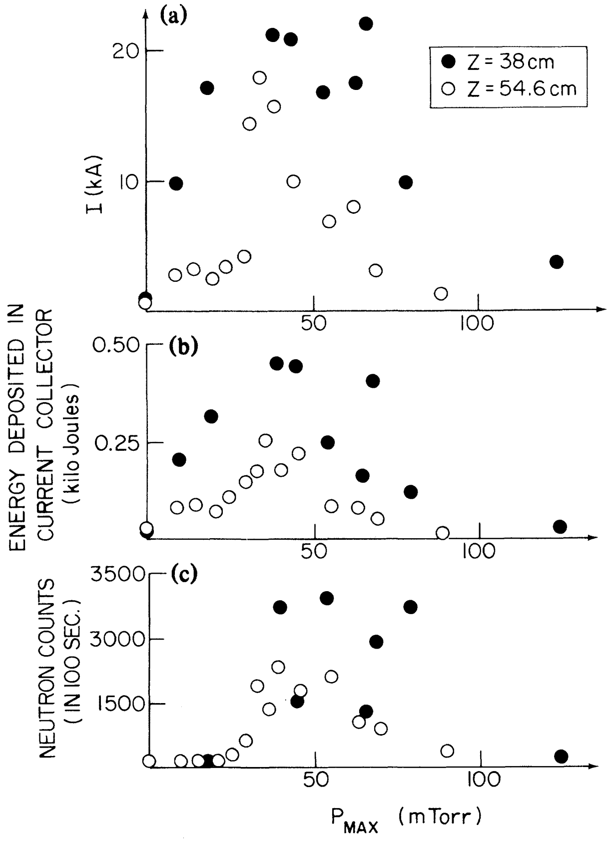

FIG. 3. Results of (a) current collector, (b) calorimeter, and (c) neutron detector measurements at $z = 38$ cm and $z = 54.6$ cm as a function of gas-cloud peak pressure ($p_{\max}$) at time of beam injection.

The current reaching a given position in the drift tube was measured with a low-impedance (14 mΩ) current collector with a carbon beam stop 7.4 cm in diameter. Figure 2 shows typical wave forms from the current collector for (a) the injected current at the anode, (b) the current at $z = 38$ cm from the anode with no gas cloud present, and (c) at $z = 38$ cm with a gas cloud at optimum pressure present at the anode.

A thermistor embedded in the carbon beam stop was used to measure the temperature rise of the beam stop which yields an estimate of the total beam energy (electrons and ions) propagated to a given axial position in the drift tube. The injected electron beam energy was approximately 1 kJ.

As an additional diagnostic, a silver-activation neutron detector was placed exterior to the drift tube and used to detect neutrons produced by accelerated protons striking the stainless-steel drift tube wall. Proton energies in excess of 5 MeV were routinely observed using foil activation diagnostics.[7]

Figure 3 shows the results obtained from all three diagnostics for beams injected through the localized gas cloud into evacuated drift tubes of axial lengths 38 and 55 cm.

Figure 4 is a photograph of a 20-mil-thick copper witness plate placed 70 cm downstream of the anode and exposed to the beam under conditions where effective beam propagation is observed. The damage pattern results from thermal effects associated with beam energy deposition. The small size (comparable to that of the anode aperture) and circular symmetry of the witness-plate damage pattern

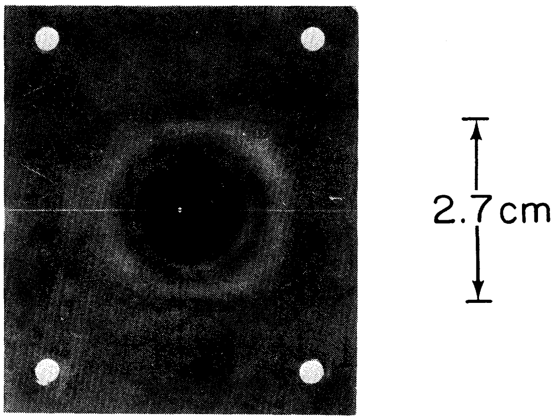

FIG. 4. Photograph of copper witness plate at $z = 70$ cm with optimized gas-cloud pressure at injection.

are a clear confirmation of the effective beam propagation due to the gas cloud at the anode.

The results of our experiments may be summarized as follows:

(1) Electron beam current in excess of the space-charge–limiting value I_L (here about 8 kA) can propagate into a vacuum drift tube if a localized source of ions is provided at the injection point.

(2) The propagation of electron beam current to a given axial position is critically dependent upon the peak pressure of the gas cloud; this implies that the propagation results from charge neutralization provided by the localized source, rather than from ions drawn off the drift tube walls or from the background vacuum.

(3) The time delay between the arrival of the electron pulse at the collector and the injected current pulse increases with distance while the width of the collector pulse decreases, indicating that the electrons arriving at the collector come from the late part of the injected beam pulse.

(4) The total energy deposited in the downstream collector at 38 cm is about 50% of the injected beam energy and decreases as the axial position of the collector is increased, even when the peak electron current collected remains about the same.

(5) Neutron production by accelerated protons seems to correlate reasonably well with effective propagation of the beam current. The propagation velocity of the front of the beam is comparable to that of the fast protons observed ($v \leqslant 0.1c$).

These conclusions support a description of the propagation process which we present here as a plausible explanation of the observed phenomena. In this concept, the electron beam enters the drift tube at a current $I > I_L$. Collisional ionization of the gas provides positive ions for charge neutralization and permits the beam to propagate to the edge of the cloud. As the beam enters the vacuum region downstream from the cloud, the space charge forms a "virtual cathode" from which the electrons are reflected back.[6,8] The high electric fields of the virtual cathode draw ions from the cloud until the electron beam can propagate further into the vacuum drift region. This process may repeat itself until a channel of ionization has been produced stretching from the anode to the collector, at which time the remaining beam electron current at the back end of the pulse may flow through the channel at nearly the speed of light and be collected. Thus, the fraction of the injected current pulse arriving at the collector depends upon the time necessary to establish the channel of ionization. As the axial position of the collector is moved further downstream, this time increases until it becomes equal to the injected current pulse duration. At this point, the current observed at the collector falls to zero.

The dependence of the propagation on the gas pressure can be explained as follows. At low pressures, ions are not available in sufficient number to achieve the partial neutralization required for efficient propagation. Thus, the beam spreads radially as it propagates, resulting in more current collected at $z = 38$ cm than at 55 cm, etc. As the injected gas pressure is increased, an optimum value is reached at which just the right amount of ions is available for adequate partial neutralization and effective propagation of the electron beam. Beyond this optimum value, a larger number of ions is available and may be accelerated at the expense of a lower peak and/or average ion velocity. Thus, given the finite pulse length of the beam (~ 30 ns), effective propagation cannot be achieved as far down the drift tube as under optimum conditions. This conclusion is supported by the drop in neutron production at high gas-puff pressures.

This process is somewhat similar to that discussed by Ryutov and Stupakov[11] in reports of experiments in which an intense electron beam is injected through an anode foil into vacuum in the presence of a strong axial magnetic field. In our experiments, however, the absence of the confining magnetic field render Ryutov's one-dimensional model (with reflecting electrons) inapplicable. Because of the difficulty in treating analytically the three-dimensional (3D) beam front and transverse electron-ion dynamics, the propagation process may be best studied by use of 2D or 3D particle-in-cell simulation codes.

The propagation of charged particles in vacuum is of fundamental interest in many areas such as astrophysics, laser fusion, ion propulsion, etc. In the absence of a charge-neutralizing plasma, it is clear from our results and the preceding discussion that free-space propagation requires comoving positive ions to assure charge and current neutrality. Thus, if an intense flux of relativistic electrons is ejected from an object (e.g., star, laser pellet) into free-space vacuum, the negative space charge forms a "mirror" reflecting the electrons back towards the surface. If a plasma is present, collective acceleration of positive ions facilitates propagation away from the surface. This process is different from ambipolar diffusion in that the relativistic electrons provide the energy source for propagation into vacuum. A large number of reflecting electrons accelerates a smaller number of ions until the electron pulse terminates (as in our experiments), the supply of ions is cut off, or the comoving ions at the front of the stream have reached the same velocity as the injected electrons[6] (in which case no further electron reflections occur at the front and a charge- and current-neutralized "plasmoid" is formed). Thus, collective ion acceleration associated with the propagation of intense electron streams into free-space vacuum could play a role in the generation of high-energy cosmic rays whose origin is still an open question.[12]

This mechanism could also explain the energetic positive ions observed in laser-target-interaction experiments[13] when the fast electrons produced in the target try to escape from the target-plasma surface. We hope that future results of our investigations will provide further understanding of the correlation between collective ion acceleration and beam propagation in vacuum.[14]

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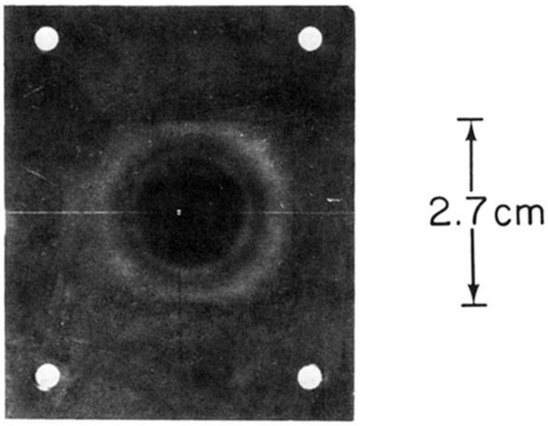
[14] A more comprehensive description of our work, including experiments with laser-produced plasmas, will be published in a separate paper.



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