Experimental study of propagation of intense relativistic electron beams in nonconducting vacuum drift tubes after passage through a localized plasma source

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The propagation of intense relativistic electron beams into evacuated nonconducting drift tubes after passage through a localized plasma source has been experimentally studied. Time-integrated photographs of the propagation process have been obtained, as well as quantitative measurements of the propagated beam current and energy.

I. INTRODUCTION

Interest in the vacuum propagation of intense electron and/or ion beams has resulted from potential applications of such beams in such areas as accelerators and new accelerator concepts,[1–4] high-power microwave and millimeter wave production,[5–7] and directed energy systems. To date, much of the work in this area has involved studies of intense beam propagation in either evacuated drift tubes where the radial confinement was provided by an axial magnetic field,[8] or in gas- or plasma-filled drift tubes where the confinement of the beam electrons is achieved via neutralizing ions.[9]

In these cases there are several important sets of physical phenomena that limit the amount of current that can be propagated in such systems. The space-charge limiting current for a beam propagating in the presence of an infinite axial magnetic field (where the beam electrons are therefore constrained to move in straight lines) is given approximately by the well-known formula of Bogdankevich and Rukhadze.[10] This result is also frequently used when no external confining magnetic field is used and the beam focusing is achieved by charge neutralizing ions:

$$I_L = \frac{4\pi\epsilon_0 m_0 c^3}{e} \frac{(\gamma^{2/3}-1)^{3/2}}{[1+2\ln(b/a)](1-f)}. \quad (1)$$

The formula is derived assuming that a beam of uniform radial density and radius a propagates inside a grounded conducting drift tube of radius b, and any fractional neutralization is denoted by f. Here m_0 is the electron rest mass and $\gamma = (1-\beta^2)^{-1/2}$ is the relativistic mass ratio for the electrons where $\beta = v/c$. Another important limit is the Alfven–Lawson[11] limit for a beam propagating through a background plasma, given by

$$I_A = \frac{4\pi\epsilon_0 m_0}{e} \frac{c^3\beta^3\gamma}{(\beta^2+f-1)}. \quad (2)$$

This limit is actually a magnetic pinch limit and it is interesting to note that for an unneutralized beam, the space-charge limited current is the lower of the two, while the Alfven–Lawson limit is the most important for charge neutralized beams.

Recently, we have initiated studies of intense electron-beam propagation into vacuum after passing through an ion source localized to the injection point. In this work neutralizing ions provide the charge neutralization necessary to allow electron-beam propagation, but, as no confining magnetic field is present, these ions must be drawn into the vacuum propagation region by the space-charge fields of the electron beam. Since both the electrons and ions in the resulting propagating beam are in motion, both charge and current neutralization effects are important, and neither of the above limiting currents can be directly applied. Previous studies[12–14] have demonstrated that currents many times the space-charge limited value can be propagated in this manner, and that surprisingly good radial focusing is achieved for both the electron and ion components of the beam.

In this paper, we present in Sec. II a review of the available theory for such a propagating electron/ion beam. In Sec. III, results of recent experiments of this type in which effective beam propagation are observed in large diameter nonconducting drift tubes (in an attempt to simulate free space propagation) are presented. This work includes the first photographs obtained of beam propagation in such systems, results that provide valuable new insight into the propagation process. Conclusions are drawn in Sec. IV.

II. REVIEW OF RELATED THEORY

There have been numerous theoretical studies and numerical simulations of experiments in which intense relativistic electron beams are injected through a localized gas cloud or other plasma source into vacuum.[15–17] These studies have primarily concentrated on understanding the processes that lead to the collective acceleration of ions to energies many times that of the injected electron energy. Most treatments have described the injection of beams with net currents several times the space-charge limiting value into a grounded drift tube and the subsequent formation of virtual cathodes immediately downstream of the injection point. The strong electric fields associated with the virtual cathode, the production of ions by electron impact and/or ion-ion avalanche processes, and the movement of the virtual cathode downstream to the edge of the localized ion source are usually used to explain the acceleration of ions into the vacuum region.

Recently, however, progress has been reported in our

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understanding of the conditions under which beams of comoving electrons and ions can propagate in vacuum without the aid of confining magnetic fields. Faehl[18] and, subsequently, Striffler, Faehl, and Zhang[19] have proposed an accessible equilibrium for such a beam in which both ions and electrons are in radial force balance. In this equilibrium, the ions are held in check by the electrostatic space-charge forces of the electrons, while the electron magnetic self-pinching force is balanced by a pressure gradient resulting from finite electron temperature and the electron density profile. In particular, assuming an axisymmetric system, the radial force balance equations for the electrons and ions may be written

electrons:

$$-en_e(E_{sr} - v_{ze}B_{s\phi}) - kT_e\frac{dn_e(r)}{dr} = 0\,, \tag{3}$$

ions:

$$eZn_i(E_{sr} - v_{zi}B_{s\phi}) - kT_i\frac{dn_i(r)}{dr} = 0\,, \tag{4}$$

where

$$E_{sr}(r) = \frac{e}{\epsilon_0 r}\int_0^r [Zn_i(r') - n_e(r')]r'\,dr'$$

and

$$B_{s\phi}(r) = \frac{\mu_0 e}{r}\int_0^r [Zn_i(r')v_{zi} - n_e(r')v_{ze}]r'\,dr'\,.$$

Under the assumption that the ion temperature is negligible, the electron and ion density distributions may be found

$$n_e(r) = \{n_0/[1 + (r/a)^2]^2\}\,, \tag{5}$$

$$Zn_i(r) = n_e(r)[(1-\beta_{zi}\beta_{ze})/(1-\beta_{zi}^2)]\,, \tag{6}$$

where

$$n_0 = \frac{8\epsilon_0 kT_e}{e^2a^2}\frac{1-\beta_{zi}^2}{(\beta_{ze}-\beta_{zi})^2}\,.$$

It is interesting to note that both of these distributions are of the Bennett type, although the coefficient n_0 is not the usual Bennett coefficient. Using consevation of energy and current, the initial electron and ion injection rates (I_0, S_i) and electron energy (V_0) were used to help determine self-consistent equilibrium beam properties downstream. In particular, for a 1-MeV, 25-kA electron beam injected into a drift tube of radius 10 a and assuming that the average electron temperature is approximately 230 keV, an equilibrium was found in which

$$0.645 \leqslant \beta_{ze} \leqslant 0.660\,,$$
$$0 \leqslant \beta_{zi} \leqslant 0.03\,,$$
$$0 \leqslant S_i/I_0 \leqslant 0.06\,,$$
$$0.957 \leqslant f \leqslant 1.00\,,$$
$$0.94 \leqslant I_{\rm net}/I_0 \leqslant 1.00\,,$$

and the required rate of ion injection was consistent with experimental values in which effective beam propagation was observed to occur.

Thus, an accessible equilibrium has been demonstrated for such a beam consistent with actual experimental numbers. The transition from the injection phase to the downstream equilibrium phase, however, is much more difficult to theoretically describe, and the experiments reported in this paper shed valuable new light on this process.

III. EXPERIMENTS

In previously reported work,[12–14] studies of intense electron-beam propagation into vacuum after passing through a localized ion source have been conducted in conducting drift tubes of various sizes. These studies have shown that effective beam propagation does occur when the density of the neutral gas cloud that serves as the ion source is set to an optimal value. Furthermore, it was shown that under optimal conditions, both the electrons and the ions in the propagating beam are remarkably radially well focused. Because it has been suggested that the presence of image currents in the conducting drift tube walls and/or of a clear return current path for the net propagated current might be necessary for such propagation to occur, we have repeated these experiments in a nonconducting drift tube of relatively large diameter. Thus, these new experimental results have been obtained under conditions which probably more closely approximate those that would be present if an intense beam were injected through a localized plasma into free space. In addition, the use of nonconducting drift tubes has allowed the first photographic studies of beam propagation in such systems.

The basic experimental configuration is shown in Fig. 1. An intense relativistic electron beam (1 MeV, 22 kA, 30 ns) is emitted from a 3-mm-diam tungsten cathode located 6.3 mm upstream of a stainless-steel anode plate. A 26-mm-diam hole in the anode plate on axis allows almost all of the electron beam to pass through the anode plane into the downstream drift region. A 30-cm-diam acrylic tube 1 m in length is evacuated to an ambient pressure in the range 10^{-4}–10^{-5} Torr and serves as the propagation drift tube. As in previous studies, a well-localized gas cloud is produced immediately downstream of the anode plane by a fast gas-puff valve. The firing delay between the puff valve and the electron-beam pulse is carefully controlled such that at the time of electron-beam injection, the localized gas cloud is confined to within 3 cm of the anode. The peak pressure of the localized gas cloud can be varied over the range 0–100

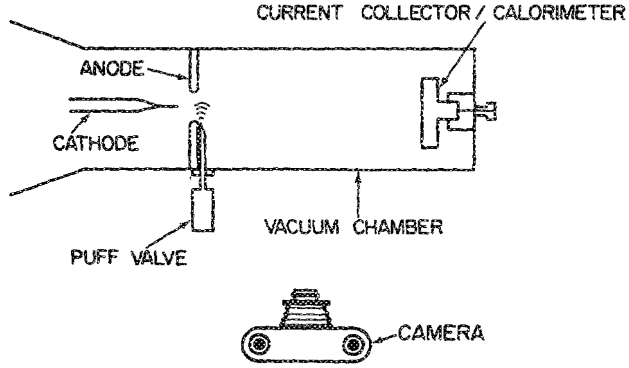

FIG. 1. Basic experimental configuration.

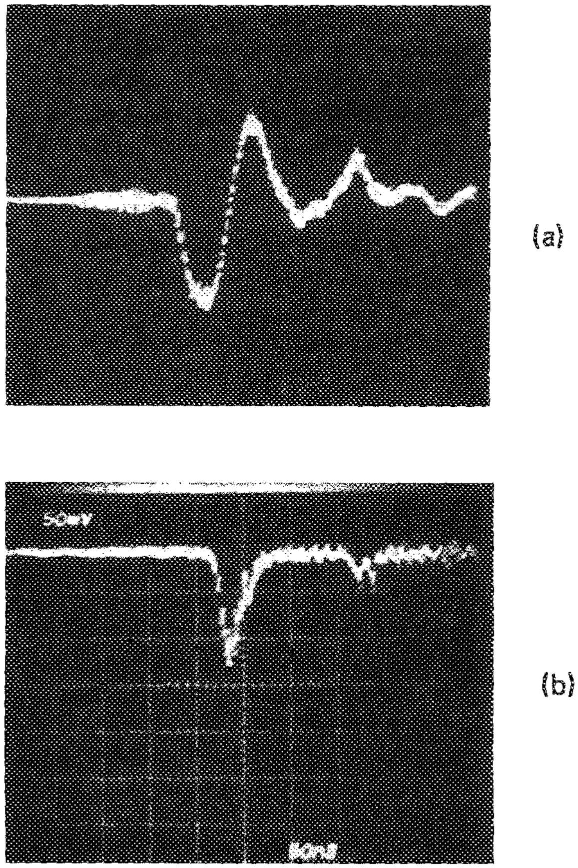

FIG. 2. (a) Diode voltage waveform. (b) Fast photodiode measurements of the time evolution of the visible light.

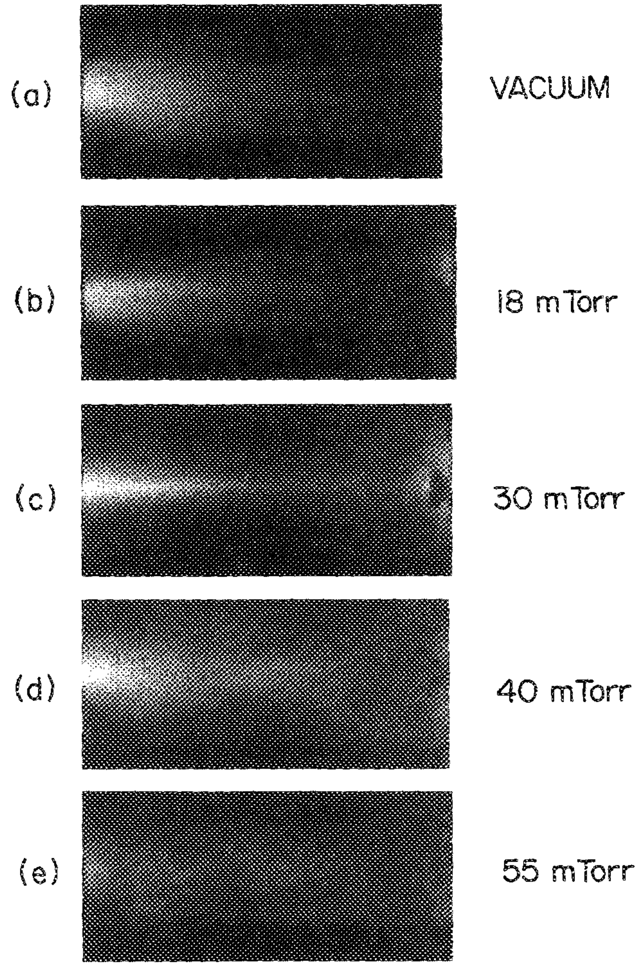

FIG. 3. Open shutter photographs taken of the propagation for several peak gas cloud pressures.

mTorr, and fast ionization gauge measurements of the pressure distribution in the gas cloud at the time of electron-beam injection have confirmed that under no experimental conditions is any significant gas pressure observed more than 4 cm downstream of the anode plate.

The current reaching a given position in the downstream drift region was measured using a specially designed low impedance current collector. To minimize secondary electron emission, a carbon beamstop was used as the current collector. A thermistor embedded in the carbon beamstop was used to measure the temperature rise of the beamstop and, therefore, obtain an estimate of the total beam energy (electrons and ions) propagating to a given axial position in the drift tube. The diameter of the carbon beamstop was 5.5 cm.

Because the drift tube was constructed from clear acrylic, open shutter photographs were taken of the light emitted from the propagating beam under various experimental conditions. Ionization of the localized gas cloud is initially achieved by electron impact ionization and subsequently by ion-ion avalanche ionization processes. The light observed, therefore, is largely attributed to radiative recombination occurring throughout the propagation process. Thus, the light observed can reasonably be expected to reflect the regions of greatest electron and ion density integrated over time. For the case where no gas was injected, ions are most likely produced by vaporization of the anode material by the electron beam. Fast photodiode measurements of the time evolution of this visible light were also made to ensure that the light observed in the open-shutter photographs was indeed generated at the time of electron-beam injection, and not a late-time plasma effect. These results, shown in Fig. 2, clearly indicate that the light observed was generated almost entirely during the primary electron-beam pulse. Other measurements, taken at much slower sweep rates, confirm that no low-level light is emitted over longer time scales. This result is significant in that such low-level light might integrate out to a more significant level than that from the primary pulse.

Open-shutter photographs taken of the propagation process are shown for several peak gas cloud pressures in Fig. 3. These photographs clearly show the rapid radial beam blowup when the beam is injected into an evacuated drift tube without a localized ion source at the injection point. As the peak pressure of the localized gas cloud is raised, however, gradually improved propagation is observed until at an optimum pressure, well-confined beam propagation is observed. Interestingly, as the peak pressure of the localized gas cloud is raised above this optimal value, the beam becomes turbulent and effective beam propagation cannot be achieved.

Quantitative measurements of the propagated beam

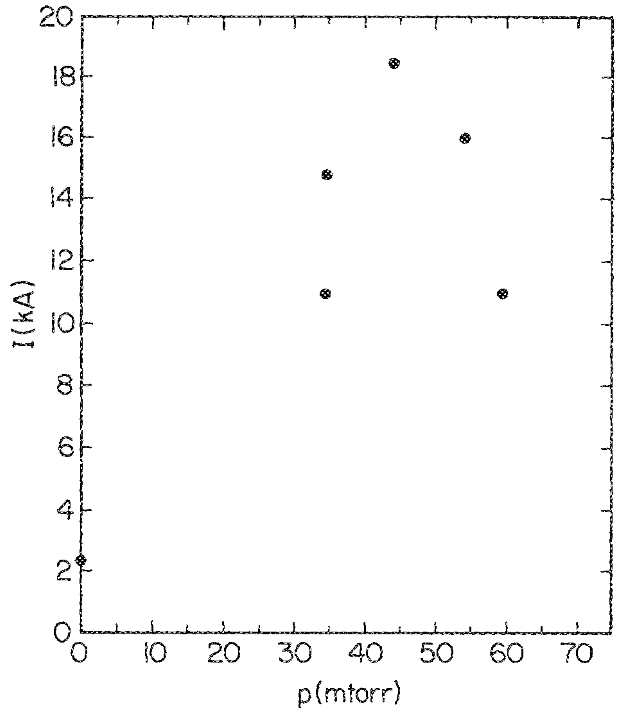

FIG. 4. Quantitative measurements of the propagated beam current at an axial position 50 cm downstream of the anode plane as a function of the peak pressure of the localized gas cloud.

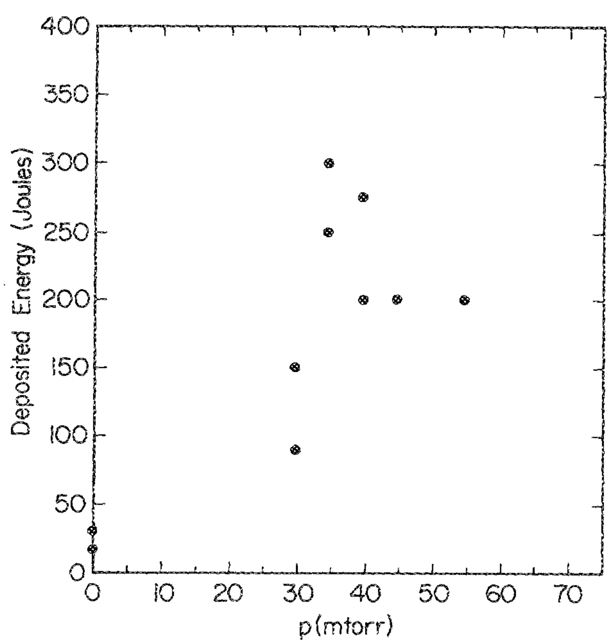

FIG. 5. Quantitative measurements of the propagated beam energy at an axial position 50 cm downstream of the anode plane as a function of the peak pressure of the localized gas cloud.

current and energy at an axial position 50 cm downstream of the anode plane as a function of the peak pressure of the localized gas cloud are shown in Figs. 4 and 5, respectively. These results clearly show that, while very little current is seen to propagate downstream when no localized plasma source is present, currents as high as 18 kA are observed downstream when the peak pressure of the localized gas cloud is set to a value of about 40 mTorr. This pressure also corresponds to the value that results in the highest net energy propagation to this point. Above this optimal value, both propagated current and energy decline as the peak gas cloud pressure is further increased.

Because it is possible that the ground connection that occurs at the current collector could influence the propagation process, the experiments were repeated with this collector completely disconnected from ground. In this case, only the energy propagated (the calorimeter temperature rise could be easily measured after each shot) and the time-integrated photographs could be obtained. Nevertheless, the results from these two diagnostics were nearly identical to those obtained with the current collector connected. As a result, therefore, we conclude that the current collector itself did not influence beam propagation.

Although the use of clear acrylic vacuum drift tubes has allowed photographic studies of this phenomena, they also could be a source of positive ions (produced by electron impact) that could influence the propagation process. To ensure that this was not the case, a series of experiments was conducted using stainless-steel drift tubes of varying diameter lined with 1-mm-thick polyethylene sheets. The current that propagated to the 50-cm point downstream of the injection point was then measured to determine if ions [primarily protons from the $(CH_2)_N$ polyethylene sheet] could migrate into the beam rapidly enough to allow propagation (no localized gas cloud was used in these studies). The measured propagated current plotted as a function of drift tube radius is shown in Fig. 6. These results conclusively demonstrate that the 30-cm-diam acrylic drift tube chosen for these ex-

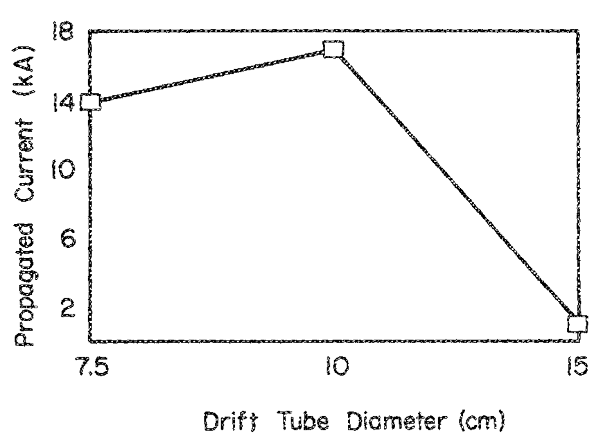

FIG. 6. Measured propagated current plotted as a function of drift tube radius for beams propagating inside dielectric-lined drift tubes (no localized gas cloud).

periments is of sufficient diameter to ensure that any ions produced at its inner surface by electron impact will not influence the injected electron-beam propagation.

IV. CONCLUSIONS

The experiments reported here shed valuable new light on a process in which charged particle beam propagation into vacuum may be achieved by injection of an intense electron beam through a localized ion source.

We have demonstrated that focusing and transport of an intense electron beam is possible without the use of extensive gas columns or externally applied focusing fields. It is clear that if the density of the ion source is optimal, the electron beam can draw out into the vacuum propagation region sufficient ions to allow for effective neutralization of the electron-beam space charge. While it is obvious that too few ions at the injection point cannot provide this necessary neutralization, the turbulence observed when the density of the ion source is above the optimal value is at present unexplained.

Although the use of nonconducting acrylic drift tubes has allowed the first photographic studies of beam propagation in such systems, the question of whether such systems really approximate injection of beams into a "free space" environment remains unanswered. Although there is nothing in the photographs to suggest any surface breakdown along the drift tube walls during the propagation process, it is difficult to definitively determine whether the drift tube remains nonconducting during the injection pulse. Interestingly, however, electron-beam damage to the drift tube was minimal on shots in which effective propagation occurred. If the vacuum tube does, in fact, remain nonconducting during the primary pulse, it is interesting to speculate as to possible return current paths for the beam electrons. Clearly a return current path through the propagating beam channel is possible, as is a path outside of the channel. Another possibility is that the return current is carried as displacement current, an idea proposed by Rhee.[20] In this event, however, the electron charge must eventually be returned to ground over longer time periods, perhaps through the plasma channel that remains after the injection pulse.

It is important to note that the two phenomena which are of fundamental importance to the propagation studies, i.e., collective ion acceleration and the creation of a high transverse beam temperature, would not occur for current injection below the space-charge limit.

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