Intense Electron Beam Dynamics in a Longitudinal Magnetic Field*

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An intense relativistic electron beam was propagated in a longitudinal magnetic field with an initial ion density less than 10^9 ions/cm^3 and a neutral density of 10^{16}–10^{17} ions/cm^3. An optimum pressure and magnetic field were found to exist for efficient beam transport, and these optima were relatively independent of current density. Possible explanations for the loss of beam electrons can be found in the retarding effects of the electric and magnetic self-fields.

Recent advances in pulsed-power technology have made possible the generation of relativistic electron beams with tens of kilojoules at a rate greater than 10^{11} W. The efficient propagation of these beams is a sensitive function of background pressure and applied magnetic field. This paper reports results of studies of an intense relativistic electron beam transport using a longitudinal magnetic field, along with possible explanations for the observed phenomena. It was found that there is an optimum applied field that, over the range of these experiments, is independent of current density and electron energy.

When intense electron beams propagate in a neutral gas with no externally applied fields, there is an electrostatic force that tends to blow the beam apart and, while the beam current is rising, there is an inductive electric field that degrades the energy of the electrons. There is also a self–magnetic-field exerting a compressive force on the beam. In practice the beam ionizes the background gas in a few nanoseconds (when the pressure is greater than 0.2 Torr) and propagates in a plasma. Ordinarily, expulsion of plasma electrons rapidly charge neutralizes the beam so the electrostatic force is dominated by the magnetic force. However, the inductive electric field and the self–magnetic-field are coupled. When the plasma conductivity is sufficient to eliminate the inductive electric field, there cannot be a self–magnetic-field because the net current is zero. For $\nu/\gamma \gg 1$, the transverse velocity of the electrons will then cause the beam to expand.[1] Here $\gamma = (1-\beta^2)^{-1/2}$, $\beta = v/c$, with c the velocity of light and v the electron velocity; and $\nu/\gamma = I_{\text{amps}}/17\,000\beta\gamma$. However, when a B_z field is applied, the electrons are constrained to follow the magnetic field. This allows the possibility of efficient transport of high-ν/γ beams over a few meters. It has been shown previously that beams can be efficiently transported at magnetic fields below 10 kG and beam currents less than 300 kA with a mean electron energy of approximately 600 keV.[2-4]

The experiments reported in this paper were carried out on the Physics International Mylar Line (PIML) and Snark Mylar line pulsers at Physics International Company.[5,6] The PIML machine was operated with a mean electron energy of 200 keV and a peak current of 200 kA. The Snark machine was operated with mean electron energies of 500 to 650 keV and peak currents of 400 to 550 kA.

These experiments used a 1.2-m solenoid with a maximum B_z variation of 3% over the area of the beam. The cathode and anode of the field emission diode were at the end of a vacuum coaxial configuration that was magnetically transparent to the pulsed B_z field and extended 10 cm into the solenoid. Targets were also magnetically transparent and were always in the uniform field region of the solenoid (Fig. 1).

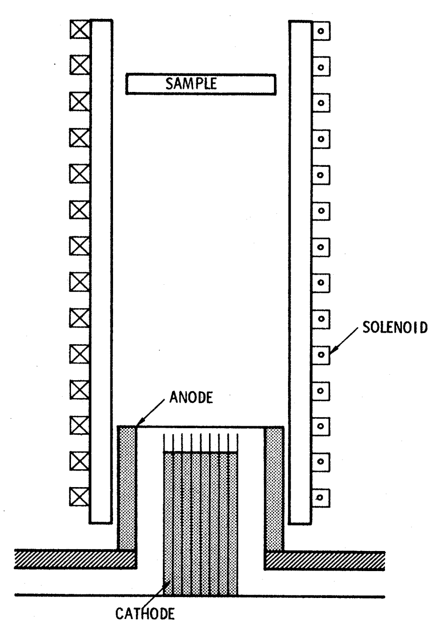

FIG. 1. Schematic diagram of the experiment.

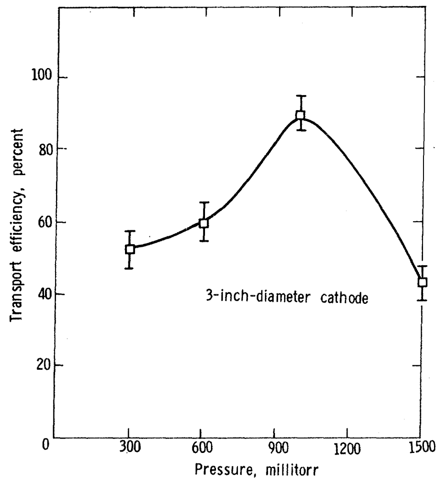

FIG. 2. Transport efficiency ζ as a function of pressure. The transport distance was 1 m, B_z was 8.9 kG, and the average current density at the anode was 9 kA/cm^2.

Transport efficiency was measured by Faraday cups and calorimeters. There was significant dispersion of the current pulse during transport due to a spread in parallel velocity as the electrons were emitted from the diode. The Faraday cup was used to determine total charge transported and the ratio, ζ, was used as a measure of transport efficiency. The measured charge and energy transport efficiencies agreed within the experimental error. Typical numbers were a charge transport efficiency of $(90 \pm 10)\%$ and an energy transport efficiency of $(80 \pm 20)\%$.

The only preionization used in these experiments was that produced by high-frequency components of the solenoid wave form. This produced an initial ion density that was less than 10^9 ions/cm^3 while the neutral density was typically 10^{16} atoms/cm^3.

Figure 2 is a plot of the transport efficiency as a function of pressure at 8.9 kG. There is an optimum at about 1 Torr with a decrease in transport efficiency on either side. Other investigators[7] have found that transport efficiency does not decrease beyond 1 Torr; however, this may be because of better preionization before the beam is injected.

Within the accuracy of the experiment, the transport efficiency ζ dropped off linearly with distance. For some conditions such as 1 Torr and 8.9 kG, the efficiency was still $(90 \pm 10)\%$ at 1 m while other parameters, such as 0.6 Torr and 8.9 kG, gave $(60 \pm 10)\%$ transport at 1 m.

Figure 3 shows the transport efficiency as a

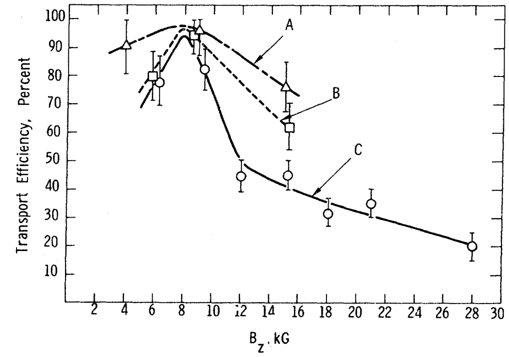

FIG. 3. Transport efficiency ζ as a function of B_z. The pressure was 1 Torr and the transport distance was 0.5 m. Curve A is for 3 kA/cm^2 on PIML, B is for 9 kA/cm^2 on Snark, and C is for 20 kA/cm^2 on Snark.

function of magnetic field for several current densities. The optimum magnetic field for beam transport is relatively insensitive to current density. Above this optimum field the transport efficiency drops off approximately as $(B_z)^{-1}$. The rate of decrease of the transport increases as the current density increases. However, preliminary data on another system indicate that efficient transport can be obtained for current densities as high as 100 kA/cm^2 and fields as high as 50 kG when the background gas has been efficiently preionized.[8]

Poor Coulomb transport efficiency is expected when some primary electrons have insufficient parallel energy to overcome the axial electric and magnetic retarding forces. The retarding electric field E_z results from incomplete current neutralization, and the magnetic mirror force results from diamagnetism of the rising beam current. Complementing these retarding forces is a small loss of parallel energy in transit through the (vaporized) anode foil (~10 keV for a $\frac{1}{2}$-mil titanium foil) and the screening foil of the Faraday cup (1–2 keV).

From measurements of the net current ($\lesssim 6\%$ of beam current for B_z below optimum, increasing for B_z above optimum), induced E_z fields upwards of 700 V/cm are expected. If this field is reasonably uniform, as indicated by comparison of net current at both ends of the transport region, then an electric potential of at least 70 kV is expected over 1 m. The magnetic force is harder to estimate because it depends on the radial component of B integrated along an electron orbit, i.e., on the rate of change of beam diamagnetism. It has been pointed out[9] that this $\vec{v} \times \vec{B}$ force may be even larger than the electric one because, although B_r is small, the mean azimuthal velocity v_θ (due to the self-field B_θ and radial electric fields) can be large, the more so when current neutralization is less complete.

At magnetic fields high enough to dominate the cross-field conductivity, the model equation $J_\theta/J_{zb}=B_\theta/B_z$ (J_θ is azimuthal beam current density; J_{zb} is primary-beam axial current density) gives[10]

$$\frac{B_r}{B_z} \sim \frac{\beta_\parallel a}{20}\,\frac{n_b^2}{n_p{}^\nu}$$

at peak B_r. Here a is the beam radius (in cm), n_b and n_p are the peak beam and plasma densities (in cm^{-3}), and ν is the effective collision frequency for plasma electrons. For the parameters of these experiments, the peak value of B_r/B_z is estimated to be about 10^{-2}, independent of B_z. Thus for $B_z=10$ kG, B_r could be of order 100 G, increasing linearly with B_z. But $B_r=100$ G, with an azimuthal velocity of beam electrons based on the model equation above, gives a retarding force equivalent to about 1 keV/cm of E_z field. Any "tying" of field lines at a conducting target could increase B_r and its corresponding retarding force. In addition, if the radial distribution of plasma return current were not the same as the beam current, a higher B_θ and hence a higher B_r retarding force would result.[9,11]

One might thus expect that electrons with parallel energy less than a few hundred keV are reflected to the diode, where they will be lost if the voltage is decreasing. There is evidence that much of the beam energy at these current densities is in transverse motion,[1,12,13] with mean angles probably of order 1 rad. Because the beam current is increasing with time for almost all of the pulse duration and because higher beam currents are often associated with a larger fraction of energy in transverse motion (thus relatively less in parallel motion) one might expect that it is mainly the final, highest-current portion of the pulse which is not transported to the detector. This is at least not inconsistent with the current wave forms at the Faraday cup and gives qualitative agreement with the magnitudes and B_z dependence of the efficiency ζ (see Fig. 2).

In conclusion, some retarding mechanisms are known which are probably important in decreasing beam transport at higher magnetic field; however, the explanation is not yet complete.

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