Erosion of a Relativistic Electron Beam Propagating in a Plasma Channel

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A relativistic electron beam has propagated 91 m in a laser-ionized plasma channel across applied magnetic fields much larger than the geomagnetic field. Beam currents ranged from 0.3 to 1.0 kA and transverse magnetic fields from 0.1 to 4.0 G. Beam degradation in the form of a shortening of the current pulse (erosion) was observed. The erosion processes were inductive and magnetic erosion. Observed total erosion rates are in agreement with the summation of the theoretical inductive and magnetic erosion rates. Magnetic erosion was enhanced when the beam radius was larger than the channel.

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The transport of a relativistic electron beam (REB) over 91 m in a laser-ionized plasma channel, across transverse magnetic fields as large as 10 times the ambient geomagnetic field, has been observed. This is the first demonstration of the efficient propagation of a long-pulse (>0.5 μs) electron beam in the ion-focused regime (IFR) across a magnetic field for distances approaching 100 m.

The steady-state loss of electrons from the front of the propagating pulse, a phenomenon peculiar to IFR transport and known as beam head erosion, was observed and measured. The speed at which the beam front recedes into the beam body is termed the erosion rate: $\beta_E = \beta - \beta_F$. Normalizing all velocities to the speed of light, β_E is the erosion rate, β is the beam velocity, and β_F is the beam front velocity. The decreasing pulse length due to erosion processes poses a critical limitation for applications that require long scale-length propagation, such as recirculating accelerators and exoatmospheric propagation. Erosion across a magnetic field was measured to be significantly enhanced when the beam diameter was greater than the channel diameter. In addition, the beam was observed to propagate efficiently and with no violent disruptions on an "overionized" channel (more channel electrons than beam electrons).

IFR transport of a relativistic electron beam in a plasma channel has been shown to be quite efficient [1–3] and, in principle, an REB in a laser-preionized channel in a low pressure gas will propagate long distances. It has been successfully employed in accelerators [4] and has applications in high-power microwave devices [5] and free-electron lasers [6].

When an electron beam is injected onto a plasma channel, the space charge of the beam expels the channel electrons while the much more massive ions remain relatively fixed. The resulting positive ion channel focuses and guides the electron beam. The strength of the channel guide force is a key parameter in the physics of IFR guiding and is characterized by the neutralization fraction $f = N_i/N_e$, where N_i is the channel ion line-charge density and N_e is the beam line-charge density.

As the electron beam propagates down an initially neutral plasma channel, the ejected channel electrons form a radial current which in turn induces a longitudinal electric field. This field slows electrons near the beam head. When these electrons lose sufficient energy, they too are lost radially. This process is axisymmetric and is termed inductive erosion [7]. If a transverse magnetic field is present, the electrons in the beam head that do not feel the full focusing force of the ion channel are lost due to the transverse Lorentz force. This loss process is not axially symmetric and is termed magnetic erosion [8]. We report here the first experiment to measure the inductive and magnetic erosion rates of a long-pulse electron beam propagating distances approaching 100 m.

The inductive erosion rate was calculated using the method of Mostrom [9], which determines that an effective erosion potential beam electron must climb through to reach the beam front. For the case of a uniform plasma channel, no background plasma, and a Gaussian beam, the inductive erosion rate is given by

$$\beta_I = \beta - \frac{\beta X(X+Y) - \sqrt{1+\beta^2X^2-(X+Y)^2}}{1+\beta^2X^2}, \tag{1}$$

where β is the normalized beam velocity, $X \equiv \gamma - \nu L_b$, and $Y \equiv \nu f L_c$. Here, γ is the relativistic factor, f is the neutralization fraction, and $\nu = I(\mathrm{A})/17\,000\beta$ is Budker's parameter. L_b and L_c are dimensionless inductances defined as

$$L_b \equiv \left[-0.11595 + \ln\left(\frac{R_W^2}{r_b^2}\right)\right], \tag{2}$$

and

$$L_c \equiv \left[1 - \frac{r_b^2}{r_c^2}(1 - e^{-r_c^2/r_b^2}) + \ln\left(\frac{R_W^2}{r_c^2}\right) + \mathrm{Ei}\left(-\frac{r_c^2}{r_b^2}\right)\right], \tag{3}$$

where r_b and r_c are the respective beam and channel radii, R_W is the wall radius, and E_i is the exponential integral.

Since magnetic erosion is not an axisymmetric process, it does not lend itself easily to an analytic derivation in regimes where it can be measured experimentally. The computer code BUCKSHOT [10], originally developed for study of IFR beam propagation, was used by Mostrom to calculate the magnetic erosion rate over a wide range of parameters. The parameter ranges studied were $5.9 < \gamma < 70$, $0.38 < I < 3$ (kA), $0.25 < f < 0.9$, $0.5 < r < 5.0$ cm, and $1 < B < 15$ G. The beam and channel were assumed to have Guassian radial density distributions of equal radii. A statistical analysis of the results showed that the magnetic erosion rate β_M varied with those parameters according to

$$\beta_M = 0.025 f^{0.020} \frac{r^{0.82} B_{\perp}^{0.90}}{\gamma^{0.49} I^{0.89}} . \quad (4)$$

This expression for the magnetic erosion rate and the inductive erosion rate given in Eq. (1) will be used for comparison with the experiments discussed in this Letter.

The total erosion rate of the electron beam was determined by measuring the pulse length eroded as it propagated down an array of current monitoring stations. The normalized erosion rate of a beam propagating past two current monitors is

$$\beta_E = \frac{\beta \delta x}{\Delta z + \delta x} , \quad (5)$$

where β is the beam velocity, δx is the length of beam eroded, and Δz is the distance between the current monitors.

The beam was allowed to propagate several betatron wavelengths to assure that it had reached radial equilibrium on the channel before measurements were taken. Current monitors were located every 14 m so that the steady-state erosion rate could be averaged over the long propagation distances available. The total current data was collected on seven LeCroy 6880 digitizers and stored and processed on a microVAX II computer.

Figure 1 shows the experimental setup. A 2.5 cm radius plasma channel with a uniform density distribution

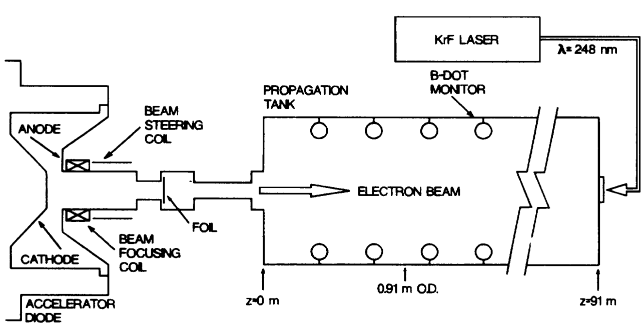

FIG. 1. Experimental setup. Four 2.5 cm diameter b-dot loops were used at each of seven current monitor stations, spaced every 14 m. Now shown are the transverse magnetic field coils, which run from 0 to 82 m. The electron beam enters from the left and the laser from the right.

was formed by photoionization using an electron beam-amplified KrF laser [11] and trimethylamine (TMA) gas at a working pressure of 3.0×10^{-5} Torr. TMA was used because it had been shown to have a large cross section for two-photon ionization by KrF laser radiation at 248 nm [12]. The laser entered the propagation tank from the opposite end of the tank as the electron beam.

The channel plasma density was measured as a function of laser energy using a microwave resonator probe [13] in a preliminary series of experiments [14]. The laser energy, and hence f, was measured for every electron beam shot. An accuracy of 20% was assigned to the measured f value.

A 2.5 MeV 0.5 μs electron beam was produced by the TROLL accelerator [15]. By timing the laser to arrive at the accelerator 150 to 200 ns into the pulse, the beam's rise time could be sharpened from 150 to less than 10 ns. The electron beam had a Gaussian density profile measured to an accuracy of ± 0.5 cm at the $z = 84$ m location using a Čerenkov diagnostic [16]. Coils on the exterior of the propagation tanks provided a uniform dc transverse magnetic field for almost the entire propagation length. The net field was varied from 0.1 to 4.0 G.

The electron beam was observed to propagate efficiently for the entire 91 m. Measurements show that there is little if any radius growth after the beam comes to equilibrium on the channel [17], indicating that the electron beam could have propagated in a pinched mode for more than 1 km.

Figure 2 is a comparison of beam current signals which includes a correction for beam time of flight. The loss of

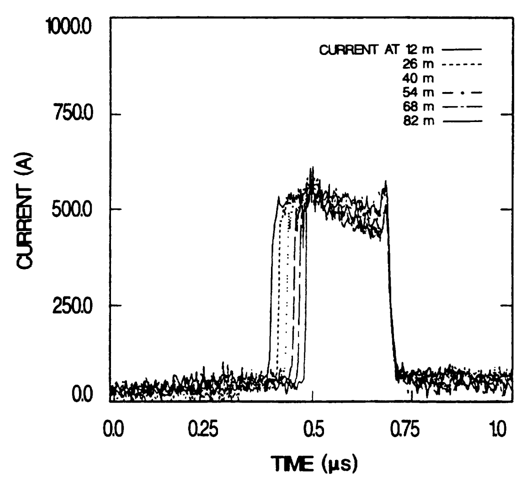

FIG. 2. Beam current as a function of time at the current monitor locations. The digitized current signals from the b-dot stations were corrected for time of flight using $\beta = 0.985$. Here, the beam was propagated across a 4.0 G transverse magnetic field. The front of the beam shows the combined effects of magnetic and inductive erosion as the beam propagates. The trailing edge of the current pulse signals typically overlay ± 2 ns.

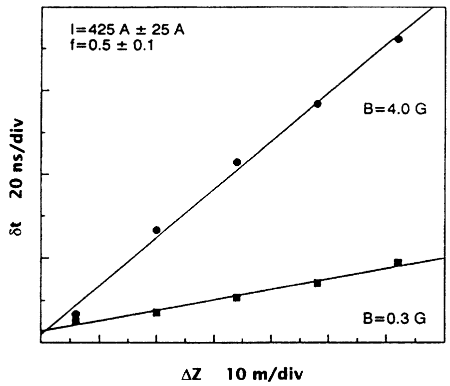

FIG. 3. Two shots of similar parameters showing the effect of the transverse magnetic field. Here, we show δt eroded as a function of the distance propagated.

pulse length at the beam head is readily apparent. The tail or trailing edge of the beam pulse typically overlays to ± 2 ns. Figure 3 is a plot of eroded pulse length as a function of propagation distance for two similar shots with different transverse magnetic fields. The erosion rate can be obtained from the slope of the plot. The difference in slopes, i.e., erosion rates, can be attributed to the increased contribution of magnetic erosion at higher field strengths. Figure 4 presents the analytic inductive erosion rate [Eq. (1)] and several experimental data points where the magnetic erosion component was minimal. Agreement is very good.

While magnetic erosion can be "turned off and on" by virtue of an externally generated transverse field, inductive erosion is always present to some degree. This complicates comparison of the observed erosion rate across a magnetic field with the inductive and magnetic erosion rate expressions presented earlier. A theoretical model which jointly describes the complex physics taking place at the beam head, and explicitly predicts how the two erosion rates combine, does not presently exist. Therefore, as a first order estimate of the total theoretical erosion rate, we use a simple sum of the inductive and magnetic erosion rates [Eqs. (1) and (4), respectively]. This gives good agreement over the broad range of parameters covered. Excluding those data where the beam was much larger than the channel, the agreement was within 16%. Better agreement may have been obtained with an expression similar to Eq. (4) but for a uniform channel and Gaussian beam.

It is interesting to note that even when f was greater than 1, the beam propagated efficiently. There is some theoretical justification for this [18], and simulations at these specific parameters showed some evidence of the transverse two-stream instability [19] but not the total disruption of beam propagation one would expect (until $f \approx 2$). The expressions for the erosion rates were derived under the assumption that $f < 1$. However, the measured f value, even if greater than 1, was used in evaluating Eqs. (1) and (4) for comparison. This is a reasonable assumption, because all of the electrons in the plasma channel would "see" the repulsive force of the beam's field and be ejected to the wall, removing energy from the beam head and contributing to erosion.

Figure 5 compares experimental data with theory, including magnetic erosion. Because of the large parameter space possible, only one or two data points are available for most sets of parameters. A source of disagreement in comparing our results with theory is Eq. (4) for the magnetic erosion rate, which assumes equal beam and channel radii. Data from the Čerenkov diagnostic indicate some shot-to-shot variation of the beam radius. Those shots in which the beam diameter was greater than

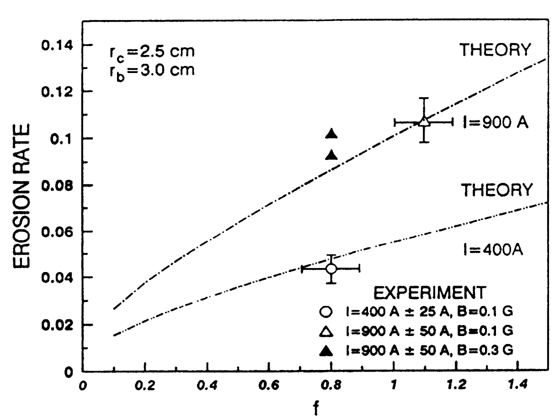

FIG. 4. Comparison of the theoretical inductive erosion rate [Eq. (1)] and experimental data points of similar parameters.

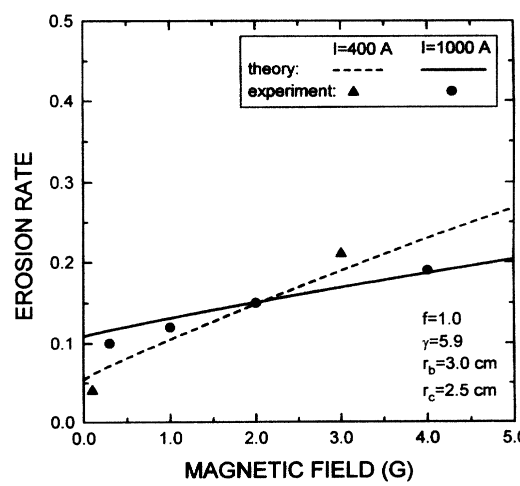

FIG. 5. Comparison of experimental data (symbols) and theory (lines). The total theoretical erosion rate is the sum of the inductive and magnetic erosion rates. The expression for magnetic erosion [Eq. (4)] assumes beam and channel Gaussian density profiles of equal radii. These conditions are not strictly met by the experiment.

the channel diameter showed a higher magnetic erosion rate than expected. This is important because long-pulse electron beams in the IFR are plagued by the ion-hose instability, which after phase mixing results in a larger beam radius [8]. Thus, propagation across a magnetic field would have the secondary detrimental effect of an enhanced erosion rate if the beam eroded into the nonlinear hose region.

In conclusion, ion-focused transport of a long-pulse electron beam in a laser-formed plasma channel has been demonstrated over 91 m. The total erosion rate for a 2.5 MeV, 0.5 μs electron beam with parameters varying in the ranges $300 < I < 1000$ A, $0.5 < f < 1.5$, and $0.1 < B < 4.0$ G has been measured. The long propagation distance and the accuracy of the time-of-flight correction made very accurate and repeatable measurements possible. The total erosion rate for a beam propagating across a transverse magnetic field was compared with available theory. From a data set of 41 shots, it was found that for the experiment's parameter regime, the sum of the theoretical erosion rates were within an average of 16% of the measured value. It was also shown that efficient propagation at $f > 1$ was possible, and magnetic erosion is enhanced when the electron beam is larger than that of the guiding plasma channel.

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