TRANSPORT AND STABILITY OF LONG-PULSE, HIGH-CURRENT ELECTRON BEAMS IN ION FOCUSED REGIME PLASMA CHANNELS FOR ADVANCED ACCELERATORS

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ABSTRACT

We present data demonstrating efficient transport (up to 76% instantaneous current transport), of long-pulse, high-current electron beams in preformed plasma channels. Channels were created by low-energy electron beam ionization of monatomic gases. These transport efficiencies are comparable to optimum values obtained in our previous long-pulse electron beam transport experiments[1,2] in laser-preionized DEA. Experimental results show development of both ion hose instability and microwave emission indicative of REB-plasma electron two-stream instability. Significant microwave emission was observed in the S-band (2.1-4.3 GHz) only when the neutralization fraction, f_e, exceeded unity.

INTRODUCTION

Pulsed, high-power relativistic electron beam (REB) technology has significant applications to advanced accelerators, the generation of high-power microwaves, plasma heating, and free electron lasers. In particular, recent advances in pulsed power technology[3] have made available electron beam generators capable of producing high-current REBs of long duration (≥ 1 μs). Electron beam research at the University of Michigan has utilized the Michigan Electron Long Beam Accelerator[1-3] (MELBA), which operates with peak parameters: 1 MV, 10 kA, and pulselengths from 1 - 1.5 μs.

High-current electron beams with microsecond pulselengths provide ideal conditions for investigating the stability of advanced accelerator transport systems. Of fundamental importance to advanced accelerators is the stable transport of the electron beam over distances on the order of meters. Accelerator transport of high-current REBs in the ion focused regime (IFR) represents an innovative transport system utilizing plasma channels created by preionizing a channel in low pressure gas. Plasma electrons are immediately expelled from the channel by the space-charge of the electron beam. The field of the remaining ions reduces the space-charge potential of the electron beam enough to allow the electrostatic repulsive and the self-magnetic field forces of the beam to cancel, allowing stable propagation.

We present results of experiments to investigate the physics involved in the interaction between a long-pulse, high-current REB with preformed, axially-uniform IFR plasma channels. The electron beam-channel plasma interactions are not as straightforward as that for short-pulse electron beams, since the timescales may now become long enough for the dynamics of the channel ions tc significantly influence the interactions.

Short-pulse electron beam transport in preformed IFR plasma channels was initially investigated using preformed channels in organic gases (benzene)[4-6] by multiphoton UV ionization. Experiments at the University of Michigan over the past 5 years have extended this technique to investigating the characteristics of long-pulse (≈ 1 μs) electron beam transport[1,2] in channels formed using a KrF excimer laser to preionize a channel in diethylaniline (DEA).

Alternatively, channel formation by a low-energy electron beam confined in a weak longitudinal magnetic field has been applied in short-pulse[7], and long-pulse[8] electron beam transport experiments. This method allows the use of monatomic gas species, rather than large organic molecules. In this paper, we report experimental results of long-pulse (350 ns) REB transport in low-energy electron beam ionized channels in monatomic gas and compare the results to previous laser-preionized channel experiments.

EXPERIMENTAL CONFIGURATION

Plasma channels have been formed by low-energy electron impact ionization of noble gases (He, Ne, Ar, Kr, Xe). As shown in the experimental configuration of Figure 1, the plasma source is a heated tungsten filament on axis, biased to -300V with respect to the transport tube (ground). The filament is immersed in the mirror region of a weak (40-100 G) pulsed magnetic field (5 ms risetime). The beam injection end of the mirror is matched to the solenoidal field of the transport tube (1 meter long, 15 cm diameter). The other end of the mirror has a larger magnetic mirror ratio to preferentially allow source electrons to be directed into the transport tube. Axial and radial plasma density profiles have been measured, as well as the temporal evolution of these channels using Langmuir probe techniques. Channel plasma density is adjustable from about 10^9 to 4×10^{11} cm^{-3} by varying the background gas pressure, the source discharge current, or the confining axial magnetic field.

In these experiments, relativistic electron beams are generated by a long-pulse Febetron pulser, operating with parameters: voltage -250 to -400 kV; diode current 1.2kA; and pulselength approximately 350 ns. Electron beams are generated from a field emission cathode emitting surface consisting of a 2 cm square array of carbon fiber bundles spaced 4 mm apart. This emitting surface is set in a Pierce-type cathode geometry with a diode gap spacing of 2 cm. A 6 μm thick aluminized mylar foil separates the diode chamber from the transport region; aluminization is always kept facing the cathode. After passing through the anode foil, the electron beam is apertured by a 1 cm radius hole in a (1 mm thick) carbon plate located 2 cm downstream from the anode foil. Typical injected electron beam currents are approximately 200 A.

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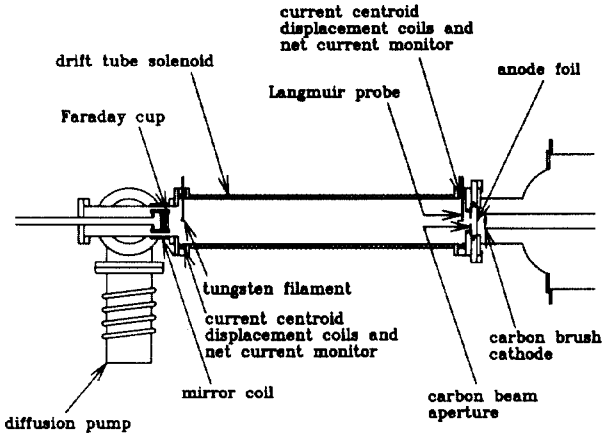


Figure 1. Experimental configuration for electron beam injection into IFR plasma channels.

Time resolved transverse motion of the electron beam is monitored with an array of B_θ-dot (Mirnov) coils located around the circumference of the transport tube. Location of the current centroid (in x-y space) is determined by two pairs of differencing coils (at right angles to each other), together with a measurement of the net current at the probe location using a Rogowski coil. Two such probes are used in these experiments. One probe, located 3 cm downstream from the carbon aperture plate, provides characterization of the electron beam at injection. The second probe is located 95 cm downstream from the injection point and monitors the behavior of the transported beam.

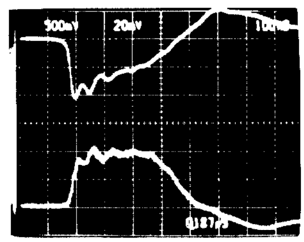
Transported beam current is measured by a fast-risetime Faraday cup comprised of a vacuum-tight assembly, which is separately evacuated by a dedicated mechanical pump. A 25.4 μm thick titanium foil discriminates against electrons below 70 keV.

Radio-frequency and microwave radiation spectra are also monitored to investigate streaming instabilities. Input signals are derived from a broadband (single turn) B_θ-dot loop. RF signals are fed to an RF spectrum analyzer which separates the signal into four frequency bands: 45 to 105 MHz; 138 to 184 MHz; 210 to 265 MHz; and 313 to 373 MHz. Microwave emissions are monitored using a series of successively higher-frequency directional couplers and diode detectors. The signal is separated into: S-band (2.1-4.3 GHz); J-band (4.4-6.6 GHz); X-band (6.6-14.25 GHz); K-band (14.3-30 GHz); and Ka-band (21.1-40 GHz).

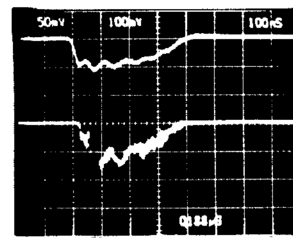
The diode region is pumped to about 2×10^{-5} Torr by an oil diffusion pump. The transport tube is separately evacuated to a base pressure of about 4×10^{-6} Torr before backfilling with the desired channel gas.

EXPERIMENTAL RESULTS AND DISCUSSION

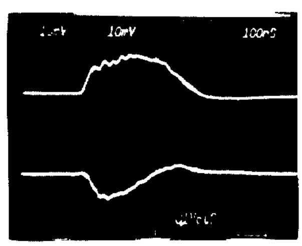
Electron beam transport results have been obtained using preionized plasma channels formed in argon at pressures of 5×10^{-5} Torr. The REB at injection is characterized by a beam current of approximately 200 A with a pulselength of 350 ns. Figure 2 presents electron beam transport data in argon. For the argon gas pressures utilized in these experiments, relativistic electron impact ionization (Δn_i) is insignificant, since $\Delta n_i/n_e \approx 0.01$ after 350 ns. For the data shown in Figure 2, the electron beam is injected into a channel with a space-charge neutralization fraction, $f_e = 1.2$, where $f_e = n_i/n_{eb}$, is the ratio of the channel ion density to the beam electron density. Efficient propagation occurs over the entire pulselength. Peak current transport efficiency is approximately 70% for this pulse, while the total fraction of electron beam charge transported for this shot was 44%. Electron beam injection into the transport tube at the same gas pressure, but without the channel plasma discharge, showed no beam transport. These results demonstrate efficient ion channel guidance and show that the low axial magnetic field does not significantly influence the beam transport.



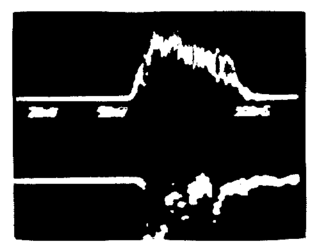
T: diode voltage (162.5 kV/div)
B: diode current (600 A/div)



T: injected net current (205 A/div)
B: transported beam current (83 A/div)



T: x-displacement (1 m) (-156/I(A) cm/div)
B: y-displacement (1 m) (196/I(A) cm/div)



T: transported net current (73 A/div)
B: S-band detector (arbitrary)

Figure 2. Experimental data showing transport results for Febetron electron beam injection into a plasma channel in argon with f_e=1.2.

Two important features are apparent in the data of Figure 2. First, the downstream current centroid displacement probe indicates a sinusoidal oscillation in the y (arbitrary) plane.Transverse oscillation of the beam current centroid is clearly illustrated. These results are consistent with transverse motion of the beam due to growth of the ion hose instability[2,8-11]. For these experimental conditions, the theoretical frequency for ion hose motion is about 4.6 MHz, which is in reasonable agreement with the experimentally observed frequency of 2.5 MHz.

Secondly, examination of the emission signal received by the RF probe in the data of Figure 2 illustrates a significant frequency component in the S-band. This radiation apparently originates from the REB-plasma electron two-stream instability. This instability can occur when the channel density becomes great enough that excess plasma electrons remain in the channel and interact with the beam electrons. Typically, this streaming instability occurs for f_e greater than unity. For f_e values on the order of 1.2, the electron plasma frequency is approximately 1.3

GHz, very near the observed signals frequency range in the S-band. Microwave signals as shown in Figure 2 were only observed on the S-band detector. No such signal was obtained for frequencies above 4.3 GHz nor below 343 MHz. Similarly no RF emission signal was observed in the S-band for f_e values below 0.8 to 0.9.

Efficient IFR electron beam transport is expected to occur for space-charge neutralization values in the range $1/\gamma^2 \leq f_e$. For a cold (i.e. zero emittance) beam in radial force equilibrium, the IFR condition is $f_e = 1/\gamma^2$, which for these experiments (γ = 1.6) occurs for $f_e \approx 0.39$. In practice, however, values of f_e greater than $1/\gamma^2$ are required to compensate for nonzero beam emittance effects. The peak current transport efficiency was as high as 76% in these experiments. For long-pulse electron beam transport, an important figure of merit characterizing the transport technique under investigation is the charge transport efficiency. We define the charge transport efficiency as the ratio of the injected electron beam charge to the transported charge.

A summary of experimental charge transport efficiency data is shown in Figure 3. This plot shows the charge transport efficiency of the preionized plasma channels in argon for f_e values in the range 0 to 1.6. As expected, efficient charge transport (> 40 %) begins around $f_e = 0.35$, in very good agreement with the initial IFR conditions of $1/\gamma^2 \approx 0.39$. The charge transport efficiency appears to saturate at about 50% for f_e values greater than 0.7.

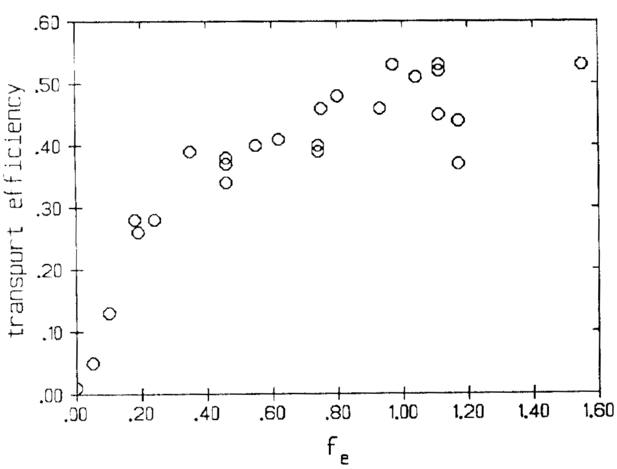


Figure 3. Experimental charge transport efficiency vs. f_e for Febetron electron beam injection into argon plasma channels.

These data can be compared to our previous experiments concerning electron beam transport in laser-induced ion channels utilizing the MELBA generator at parameters: V=0.8 MV, I=200-300 A, and pulselength of ≈ 1 µs. In those experiments the gas pressure was much higher, so electron impact ionization increased the channel ion density during the pulse. The present experiments have operated at pressures low enough that electron impact ionization is negligible. Peak electron beam current transport efficiencies in the previous laser ion channel guiding experiments were as high as 80%, compared to 76% in the present experiments. These experiments demonstrate that ion channel guidance is an effective means of transporting long-pulse, high-current electron beams in advanced accelerators. However, the neutralization fraction, f_e, must be controlled to be less than one in order to avoid streaming instabilities.

ACKNOWLEDGEMENTS

This research was supported in part by the Strategic Defense Initiative Office, the Office of Naval Research, and the National Science Foundation.

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REFERENCES

1 R.F. Lucey, Jr., R.M. Gilgenbach, J.E. Tucker, and C.L. Enloe, Laser and Part. Beams **6**, 687 (1988)
2 R.F. Lucey, Jr., R.M. Gilgenbach, J.D. Miller, J.E. Tucker, and R.A. Bosch, Phys. Fluids B **1**, 430 (1989)
3 R.M. Gilgenbach et al., Fifth IEEE Pulsed Power Conference, Arlington, Virginia, 1985 (IEEE Catalog No. 85C2121-2) pg. 26
4 W.E. Martin, G.J. Caporaso, W.M. Fawley, D. Prosnitz, and A.G. Cole, Phys. Rev. Lett. **54**,685 (1985)
5 G.J. Caporaso, F. Rainer, W.E. Martin, D.S. Prono, and A.G. Cole, Phys. Rev. Lett. **57**, 1591 (1986)
6 R.L. Carlson, S.W. Downey, and D.C. Moir, J. Appl. Phys. **61**, 12 (1986)
7 J.R. Smith and R.F. Schneider, in *High Brightness Accelerators*, Proceedings of a NATO Advanced Study Institute, A.K. Hyder, M.F. Rose, and A.H. Guenther editors (Plenum Press, New York, 1988) pg. 785
8 K.J. O'Brien, G.W. Kamin, T.R. Lockner, J.S. Wagner, I.R. Shokair, P.D. Kiekel, I. Molina, D.J. Armistead, S. Hogeland, E.T. Powell, and R.J. Lipinski, Phys. Rev. Lett. **60**, 1278 (1988)
9 K.J. O'Brien, J. Appl. Phys. **65**, 9 (1989)
10 R.A. Bosch and R.M. Gilgenbach, Phys. Fluids **31**, 634 (1988)
11 R.A. Bosch and R.M. Gilgenbach, Phys. Fluids **31**, 2006 (1988)