

Observation of Plasma Wakefield Effects During High-Current Relativistic Electron Beam Transport

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Abstract

Modulation of the beam current has been observed during ion focused regime (IFR) transport of a high-power relativistic electron beam immersed in a low-density background plasma. In this experiment, a 1.6 MeV, 1 kA, risetime sharpened electron beam is propagated on a KrF excimer laser produced IFR channel in TMA gas which is immersed in a low-density plasma filled transport tube. We present experimental measurements demonstrating modulation of this high-current relativistic electron beam near the background plasma frequency.

I. INTRODUCTION

Plasma wakefields are well known in the high-energy physics community. The plasma wakefield accelerator (PWFA)¹ utilizes the longitudinal electric fields in plasma waves excited by a short duration bunched relativistic electron beam as a source of high accelerating gradients. In the PWFA a low-current driver beam is utilized to excite the wakefields used to modify a low-current trailing beam.^{2,3} We report here experimental measurements on high-current (kA level) relativistic electron beams whose transport is strongly influenced by the self-induced wakefields.

A relativistic electron beam injected into a preionized plasma channel causes channel electrons to be expelled by the electrostatic force generated by the head of the beam and permits stable electron beam transport.^{4,8} If the plasma channel is immersed in a low-density background plasma, both channel electrons and plasma electrons are ejected by the beam head provided the combined channel and background plasma density is less than the beam density. These electrons are expelled out to the charge neutralization radius, at which point the total enclosed ion charge is equal to the beam charge. The charge neutralization radius is given by

$$r_n = r_b \sqrt{\left[\left(\frac{r_c}{r_b} \right)^2 + \frac{(1 - (r_c / r_b)^2 f_e)}{g} \right]} \quad (1)$$

where r_b is the beam radius, r_c is the channel radius, $f_e = n_c/n_b$ is the space charge neutralization fraction and is the ratio of the channel ion density to the electron beam density, and $g = n_p/n_b$ is the ratio of the ion density outside the channel to the electron beam density. A beam with an extremely long

risetime may produce such an equilibrium, but for beams with finite risetimes, typically the ejected electrons will overshoot the neutralization radius. The resulting charge imbalance causes them to oscillate about this radius at a frequency near that of the electron plasma frequency of the low-density background plasma, $\omega_p = (n_p e^2 / \epsilon_0 m_e)^{1/2}$. These radial plasma oscillations produce an electrostatic wakefield with electric field components in the radial and axial directions. The longitudinal component of this field, traveling with the beam causes accelerating and decelerating forces on beam electrons leading to beam energy and current modulation. These effects were first observed for high-current beams in computer simulations⁹ and were seen to lead to eventual beam disruption. Most of what is known about this beam-plasma interaction is due to analytical calculations^{10,11} and numerical simulations^{9,11} with very few direct experimental measurements.

II. EXPERIMENT

In the experiment, a 1.7 MeV, 6 kA, 30 ns electron beam produced by a Febetron 705 is passed through a beam risetime sharpener and matched onto a laser produced IFR channel in trimethylamine (TMA) gas. Figure 1 is a schematic diagram of the experiment. The electron beam is generated from a 2.5 cm diam velvet cathode and is extracted into a beam risetime sharpening cell through a 0.6 μ m aluminized mylar anode foil. The risetime sharpener cell¹² uses a single magnetic lens to preferentially focus the high energy portion of the beam at an aperture. This results in a 1 kA electron beam exiting the risetime sharpening cell through a second aluminized mylar foil in front of the 3 cm diam graphite aperture plate, with a 5 ns risetime and a 13 ns flat-top. The beam extracted through this aperture is matched onto a KrF excimer laser ionized IFR channel.

The 3 cm diam laser ionized channel was formed by two-step photoionization of TMA using a 750 mJ, 248 nm, 30 ns KrF excimer laser. The TMA gas flowed through the transport chamber continuously to provide a stable gas pressure in the range 0.2 - 0.8 mTorr. These TMA pressures resulted in space-charge neutralization fractions in the range $\gamma^2 \leq f_e \leq 1$, where γ is the usual Lorentz factor, sufficient to efficiently propagate the electron beam in the absence of a background plasma. The beam risetime sharpener cell and the diode region were maintained at a lower pressure, on the order of 10^{-5} Torr, to prevent diode shorting or gas focusing effects. The TMA pressure was measured with ionization gauges calibrated to a Baratron capacitance manometer. The laser was fired to

ionize the TMA typically 500 ns before the voltage was applied to the diode.

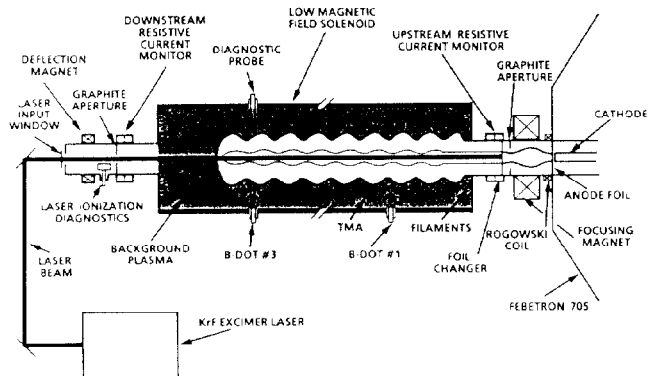


Figure 1 Schematic of the plasma wakefield experiment.

The laser produced channel is centered in a 0.5 m diam, 3.6 m long plasma filled transport chamber. The low-density background plasma filling the transport chamber is generated by a hot filament discharge in the low pressure TMA gas. The discharge is pulsed for times on the order of 1 ms to reduce the possibility of TMA fragmentation before the laser is fired. The gas pressure is low enough that beam-induced ionization of the TMA is negligible. Plasma characteristics measured by Langmuir¹³ and microwave resonator¹⁴ probe techniques indicate that the plasma has good uniformity axially, radially, and azimuthally.¹⁵ A low axial magnetic field (on the order of 5 G) is present for plasma confinement and to improve the uniformity. This field is sufficiently small so as not to influence the electron beam dynamics. The plasma density is adjustable in the range 10^8 to 5×10^9 cm⁻³.

The beam current is monitored prior to injection into the plasma filled transport chamber and after exiting the chamber by resistive wall current monitors.¹⁶ Uncalibrated, single-turn B-dot loops located axially along the transport chamber monitor the evolution of the modulation of the current. It should be noted that both monitors are sensitive to the net current flowing in the transport chamber. A scintillator-photodiode observed the x-ray signal emitted when the beam electrons were deflected to the wall at the end of the transport chamber before striking the laser input window.

III. EXPERIMENTAL RESULTS

Initial experimental measurements have demonstrated very well defined current oscillations impressed upon the electron beam after traversing the 3.6 m long transport chamber. These oscillations are in the range 150 to 300 MHz and are very close to the electron plasma frequency of the low density background plasma. In the absence of the background plasma, the most efficient electron beam transport occurred for a space-charge neutralization fraction of $f_c \approx 0.9$ as determined by the laser channel ionization measurements. This is indicative of a

fairly high transverse beam temperature and is common to electron beams generated and propagated using these techniques.

The evolution of the current oscillations is characterized in the typical waveforms shown in Fig. 2. Figure 2(a) shows the response of the resistive wall current monitors in the absence of the background plasma. The currents are shown prior to the entrance of the beam into the transport chamber (upper waveform) and after exiting the chamber (lower waveform).

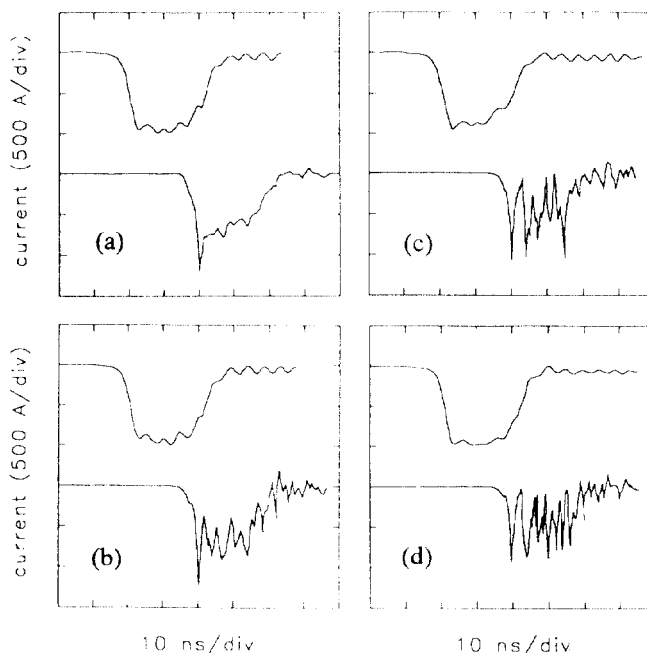


Figure 2 Current waveforms from the resistive wall current monitors; (a) $n_p=0$, (b) $n_p=4.0 \times 10^8$ cm⁻³, (c) $n_p=5.9 \times 10^8$ cm⁻³, (d) $n_p=7.9 \times 10^8$ cm⁻³. Top (bottom) waveform: current entering (exiting) the transport chamber.

Examination of the transported current waveform indicates a steepening of the current risetime with an associated spike at the front end of the pulse. This is due to a combination of inductive beam erosion and the fact that the beam voltage pulse is nearly sinusoidal and varies throughout the current pulse. Figures 2(b)-(d) illustrate the development of current oscillations with increasing background plasma density. The space charge neutralization fraction at the peak beam current for all the data presented here was $f_c \approx 0.9$, giving a neutralization radius, r_n , ranging from 4.4 cm (Fig. 2(b)) to 3.3 cm (Fig. 2(d)). The data in Figs. 2(c) and (d) indicate that the current becomes severely modulated after only 3.6 m of transport in the plasma background. Increasing the plasma density higher than that shown in Fig. 2(d) resulted in loss of transport efficiency and eventual beam disruption as indicated by the current monitors and the x-ray signal picked up by the scintillator-photodiode.

The frequency of oscillation is more readily determined from the unintegrated B-dot loop data. Figure 3 shows the

unintegrated B-dot loop response from the probe located 0.9 m downstream from the entrance to the plasma-filled transport chamber. The current oscillations are quite clear and indicate an increasing frequency with increasing plasma density.

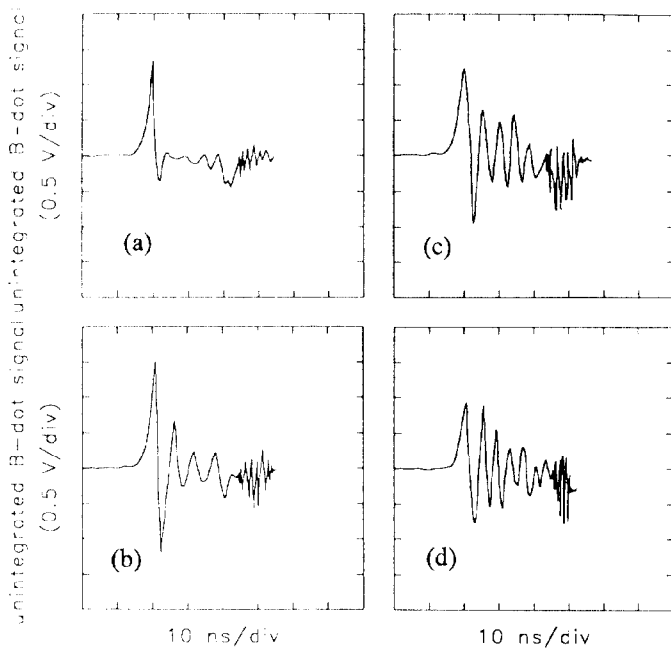


Figure 3 Unintegrated B-dot loop response 0.9 m downstream from the entrance to the transport chamber; (a) $n_p=0$, (b) $n_p=2.5 \times 10^8 \text{ cm}^{-3}$, (c) $n_p=4.0 \times 10^8 \text{ cm}^{-3}$, (d) $n_p=5.9 \times 10^8 \text{ cm}^{-3}$.

Detailed analysis of the signals is currently in progress.

IV. CONCLUSIONS

We have observed very well-defined current oscillations impressed upon a high-current relativistic electron beam propagating in an IFR channel immersed in a low-density background plasma. Severe effects on beam current transport have been observed for g parameter values in the range 0.01 to 0.03 after only 3.6 m of beam transport. Initial results indicate the frequency of current oscillation to be near the plasma frequency of the low-density background plasma, consistent with the predictions of plasma wakefield theory and simulation.

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