PLASMA CHANNELS USED FOR RELATIVISTIC ELECTRON BEAM TRANSPORT

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Abstract

Relativistic electron beam transport via plasma channels has been successfully utilized in linear induction accelerators and has been proposed for several other accelerator applications. Beams transported in such a manner are in the ion focusing regime (IFR) of propagation. In order to achieve some level of control over this method, and more completely understand its limitations, a parameter study of beam transport in a well diagnosed channel is required. A channel particularly amenable for such a study has been created by ionization of a low pressure gas with low energy electrons. Using this approach, it is possible to produce channels with suitable ion densities on a dc basis in a wide range of gases. In this report channel density profile measurements are presented. Beam transport characteristics are observed by injection of a relativistic electron beam (700 kV, 2 kA, 100 ns) into the channels.

Introduction

Electron beams are transported by ion focusing as follows. The beam is injected into a plasma channel. At the head of the beam, high electric fields eject plasma electrons leaving a channel of positive charge. This ion channel reduces beam expansion due to beam space charge and transverse temperature, such that a net focusing force is present and the body of the beam may propagate efficiently. The condition required for a focusing force for a beam with a Bennett density profile may be expressed as[1]

$$f_e \geq \frac{1}{\gamma^2} + \frac{2T_\perp}{\nu mc^2} . \tag{1}$$

The space charge neutralization fraction is defined as

$$f_e \equiv N_i/N_b , \tag{2}$$

where N_i is the line density of ions and N_b is the line density of beam electrons. For $0 \leq f_e \leq 1$, it is the degree to which a background of ions reduces the beam's space charge field. Also, γ is the relativistic factor, $T_\perp$ is the beam's transverse temperature, ν is Budker's parameter, m is the electron mass, and c is the speed of light. The assumptions made here are no beam rotation and no current neutralization. If the "greater than" situation exists, the condition for radial force equilibrium is exceeded and the beam electrons oscillate (betatron oscillations) within a beam envelope but still propagate. The necessary ion density for a focused beam depends on beam current, beam voltage, and transverse temperature.

As seen from Eq. 1, the space charge neutralization value is important in determining conditions necessary for IFR beam transport. Also it is critical in the evaluation of instabilities (e.g. the ion hose instability[2]) and beam erosion[3]. For instance, the oscillation frequency of the ion hose instability depends on f_e, as does the beam erosion rate. Therefore in most research dealing with IFR transport the question "What is f_e?" arises. Usually a theoretically determined value for f_e is rendered. In this work we seek to make detailed measurements of the ion density profile from which the ion line density can be calculated and f_e can be determined. Profiles at various density levels for each gas are presented. Beam transport is measured for each case. Much work has previously been performed in IFR transport where the channel parameters are estimated. The significance of this research lies in the study of beam transport in a channel where f_e has been experimentally determined.

Channel Measurements

The plasma channel is produced in a 15 cm diameter stainless steel tube that is 2 m long. The tube is evacuated to a base pressure on the middle of the 10^{-6} Torr range and then gas is flowed raising the pressure to the desired level. For hydrogen the gas pressure was adjusted to 2×10^{-4} Torr and for argon to 1×10^{-4} Torr. The electron gun consists of a tungsten filament heated to a temperature between 3200 and 3600°F. The filament is biased to -400 volts. An axial magnetic field of 140 Gauss guides the electrons emitted from the gun so that gas in a channel, rather than in the entire tube, is ionized. The channel was diagnosed with a Langmuir probe which uses a platinum tip in order to minimize secondary emission. The probe dimensions are 2 mm long by 1 mm diameter. A curve tracer was used both to bias the probe in the range from -25 to +25 volts and to record the probe current. The probe's radial position was adjustable so that $n_i(r)$ could easily be measured and also so that the probe could be retracted for firing of the accelerator. Density profiles are given in Fig. 1 for hydrogen and in Fig. 2 for argon. For each gas four ion channels (A-D) are given. The ion density was varied by changing the temperature of the filament (i.e. current through the filament) rather than by adjustment of the bias voltage or gas pressure.

Beam Transport

Attached to the tube end opposite of the filament was the Transbeam accelerator. The diode consists of a 7.5 cm diameter carbon cathode and an anode constructed of 0.7 cm thick carbon with a 2 cm diameter aperture on center. The gas was flowed from the filament end of the tube and was pumped through the anode aperture by the diode's vacuum system. The beamline has two Rogowski coils that

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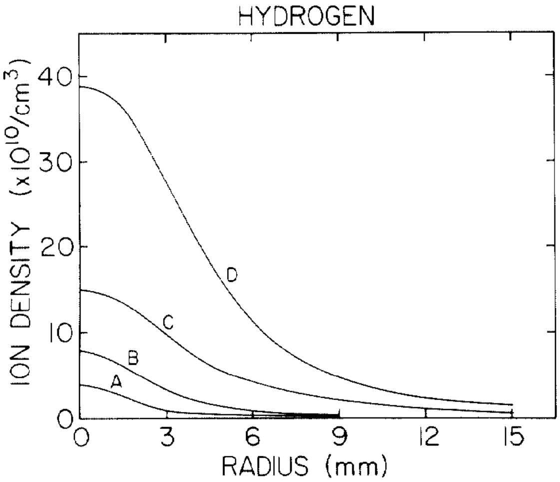

Fig. 1. Ion density profiles for hydrogen gas.

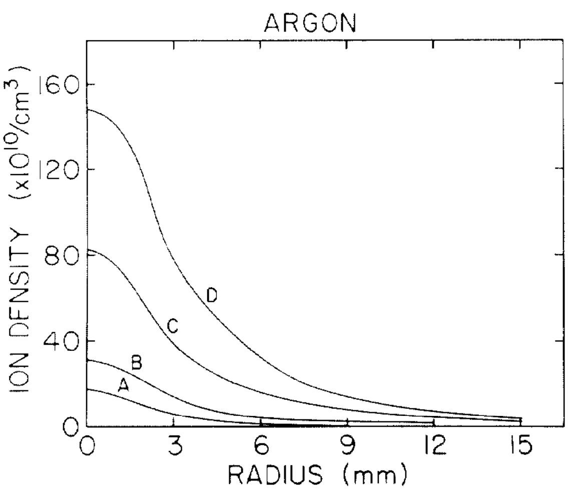

Fig. 2. Ion density profiles for argon gas.

monitor net current, which is essentially the beam current in our case. Rogowski 1 is positioned 34 cm downstream of the anode plate and Rogowski 2 is 160 cm downstream. Midway between the two Rogowski coils is an X-Y displacement monitor used for measuring beam oscillations. The Rogowski signals for IFR transport in the channels characterized in Figs. 1 and 2 are given in Figs. 3 and 4.

Discussion

The results for this report are summarized in Table 1. The percent charge transport is the ratio of the charge recorded by Rogowski 2 to that recorded by Rogowski 1. The ion line density was calculated from the profiles of Figs. 1 and 2, and the beam line density was calculated using the peak current of the upstream current monitor (Rogowski 1). The results here represent an initial stage of research in this area, therefore instead of a set of final conclusions we offer a list of pertinent observations and comments.

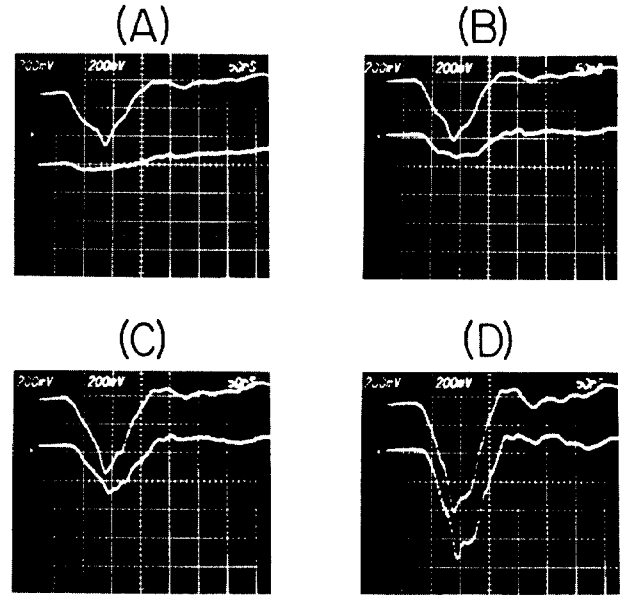

Fig 3. Rogowski signals for beam transport in hydrogen gas. The upper trace is from Rogowski 1 (0.5 kA/div) and the lower trace is from Rogowski 2 (0.6 kA/div). 50 ns/div.

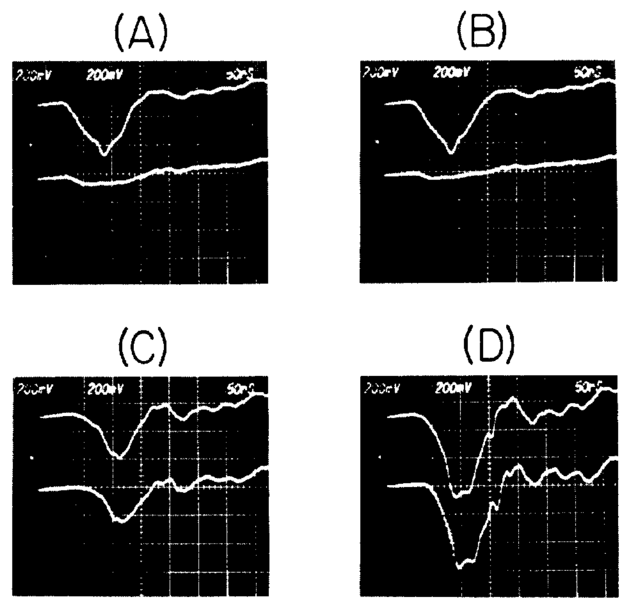

Fig. 4 Rogowski signals for beam transport in argon gas. The upper trace is from Rogowski 1 (0.5 kA/div) and the lower trace is from Rogowski 2 (0.6 kA/div). 50 ns/div.

a) Hydrogen Shots: For f_e of a tenth or less (channels A and B) low to moderate transport efficiency was observed. For channel D, where f_e equals 0.8, high transport efficiency was observed. As f_e approaches 1, current enhancement caused by an electron-electron two stream instability may result in greater than 100% transport efficiency. This was the case for channel D.

b) Argon Shots: For f_e of 0.3 (channel A) low transport efficiency was observed. The low transport efficiency for channel B, where f_e = 0.7, is due to an anomalous shot. For channels C and D, where f_e is greater than 1, the charge transport efficiency is high. Note that as f_e approaches 1, plasma electrons are not ejected effectively and they may remain in the channel. Therefore, although f_e may be greater than 1, the ratio of net ion line-charge density to beam line-charge density does not exceed 1. So we interpret the case for f_e greater than 1 to mean full neutralization of the beam's space charge.

c) For all of the channels listed in Table 1 almost no transverse beam displacement was recorded with the X-Y displacement monitor. We have observed beam displacement and oscillations in other work where the ion line density and other conditions were similar to those used in this work, but the ambient gas pressure was higher. We hope to resolve this puzzle in future work.

d) For determination of $n_i(r)$ from the Langmuir probe data electron temperature is required. For a typical channel, the plasma electron temperature varied from 2 eV at r = 0, to 5 eV at r = 12 mm. For accurate measurements it is necessary to find electron temperature at each radial position, not just at r = 0.

e) For calculation of ion line density it is necessary to measure the profile of each channel since the profiles are not identical for all channels. A measurement of only peak density is not sufficient.

Table 1.

Channel		Charge Transported (%)	N_i (#/cm)	f_e
H_2	A	20	9.5×10^{9}	0.04
	B	60	3.5×10^{10}	0.1
	C	80	1.5×10^{11}	0.4
	D	110	3.7×10^{11}	0.8
Ar	A	30	7.2×10^{10}	0.3
	B	20	1.7×10^{11}	0.7
	C	90	5.6×10^{11}	2.6
	D	120	1.1×10^{12}	2.9

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