CURRENT MEASUREMENTS IN A GAS FILLED DRIFT TUBE

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Abstract

We report systematic measurement of currents in a low pressure, gas-filled drift tube into which an intense relativistic electron beam is injected. Typically, a 0.5 MeV, 80 kA, 100 ns electron beam of 2.54 cm diam is injected through a foil anode into a gas-filled drift tube of 15 cm diam. We observe that as gas pressure in the drift tube increases, the magnitude of the net current increases up to a peak value, and then decreases. The pressure at which this peak value is achieved is interpreted as the critical pressure required for full charge neutralization of the beam. Above this critical gas pressure, the waveform of the current decays nearly exponentially with a slow time constant. The decay time constant is attributed to L/R of the drift tube and plasma column, and the resistivity of the plasma can be conveniently inferred from the time constant.

Introduction

The propagation of intense relativistic electron beams (IREBs) through a neutral gas is governed largely by charge and current neutralization processes, resulting in a complex time and space dependent distribution in the drift tube. Improving our understanding of the behavior of these beams is of current interest as these processes play an important role in many phenomena now being studied[1], such as collective ion acceleration and the general problem of the propagation of IREBs into a neutral gas. Here, preliminary studies concerning basic beam behavior are presented. In particular, the effects of background gas pressure on beam propagation and behavior are examined for various gases.

Beam propagation depends strongly on the space charge neutralization process, i.e., on how quickly the beam can ionize the gas, expelling secondary electrons until a full charge neutralizing background is created. The electron collisional ionization time[2] may be written as $\tau_e = (pS_e\beta_e c)^{-1}$, where p is the pressure in Torr, S_e is the number of ion pairs created per cm per Torr, β_e is the usual relativistic factor, and c is the speed of light. This gives the time for a beam electron to ionize the gas; any such ions created by the beam will then act to ionize the background gas themselves, creating an effective ion avalanching process.[2] Using data from Rieke and Prepejchal[3], τ_e may be found in terms of pressure as $\tau_e = \alpha/p$, where α is a constant. For example, using hydrogen gas and a beam energy of 0.5 MeV, we obtain $\tau_e = 5.2/p$ ns. Assuming electron impact ionization to be the dominant process, the rate of ionization[2,4] is governed by

$$\frac{\partial n_i}{\partial t} = \frac{n_b}{\tau_e}. \tag{1}$$

Assuming a square beam pulse, i.e., n_b is constant during the pulse length t_b, we then integrate to get $n_i = n_b pt/\alpha$, $t < t_b$. The charge neutralization fraction can now be written as

$$f_e = \frac{n_i}{n_b} = \frac{pt}{\alpha} \tag{2}$$

When the beam is fully charge neutralized ($f_e = 1$), at $t = t_b$ we can then rewrite Eq. (2) as:

$$P_c = \frac{\alpha}{t_b} \tag{3}$$

This is the critical pressure for full charge neutralization of the beam, i.e., it is the pressure, P_c, at which there is just enough background neutral gas so that full space-charge neutralization of the beam occurs at the tail. Above this pressure, other processes such as plasma return current[4,5] act to reduce the magnitude of the injected beam current.

A knowledge of the behavior of the plasma in the drift region is also important in understanding the overall processes involved in beam propagation through a gas. An analysis of the current waveforms themselves can yield important information. For instance, the decay time of the net current signal can be used to obtain the plasma resistivity. Through such relatively uncomplicated analysis, the dynamic processes involved in the beam-gas interactions can be examined qualitatively, and serve to verify and enhance our understanding of the general problem of electron beam injection into a neutral gas.

Experimental Setup

Figure 1 shows a schematic of the experimental setup used.

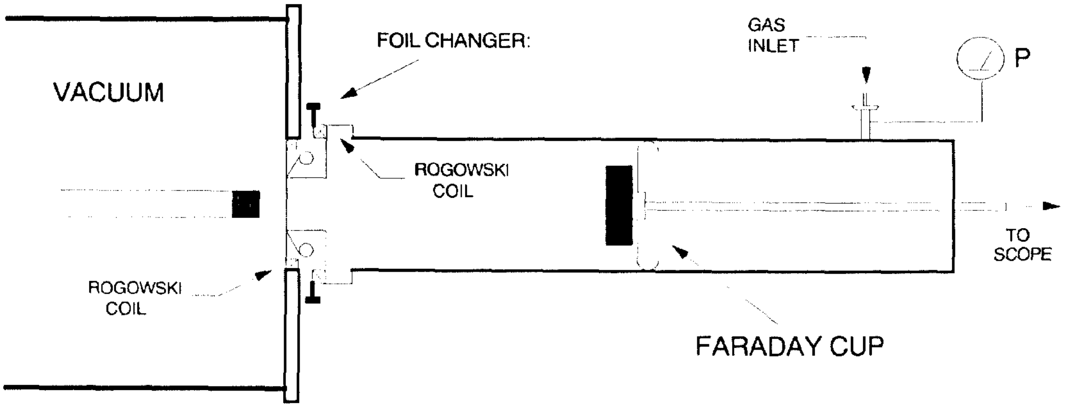

Fig. 1. Schematic of the experimental set up.

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Typically, a 0.5 MeV, 100 kA, 100 ns electron beam is injected through a foil anode into a drift tube of 15 cm diam. The diode consists of a 2.54 cm diam stainless steel cathode and an anode of thin aluminized mylar foil. The anode-cathode gap used is 7 mm. Reproducibility of the experiments was improved by using a specially designed anode system with a foil advancing mechanism which allows the production of many shots without disturbing the vacuum conditions. Two fast Rogowski coils ($L/R < 1$ ns), are also built into the system. The upstream coil measures the diode current, I_d; the downstream coil measures the net beam current, I_{net}. A Faraday cup, which is movable down the length of the drift tube, is used to measure the propagated current at various distances from the anode plane. This Faraday cup is also specially designed, with a thin, stainless steel radial resistor of low inductance (risetime is < 1 ns).

Results and Discussions

Experiments were performed to determine the magnitude of the peak injected current, I_p, as a function of gas fill pressure in the drift tube for a variety of gases. Figure 2 shows the results for argon. Using the electron collisional ionization time, we find that the argon gas pressure, P_c, which provides the amount of background gas pressure needed to just fully charge neutralize the 100 ns long beam pulse is predicted to be 11 mTorr. Values for the critical pressure for various gases are tabulated in Table I. Again looking at Fig. 2, we see that the peak injected current increases in a linear fashion as gas pressure in the drift tube is increased. This continues until the pressure reaches the critical pressure $P_c = 11$ mTorr; at this point the entire beam is propagated into the drift tube and I_p equals approximately the peak diode current, I_d, as measured by the upstream Rogowski coil in Fig. 1. Above this pressure, there is more than enough background gas to charge neutralize the beam, and other processes, such as plasma return currents induced by the beam front electric field, begin to take effect which act to reduce the beam injected current.

This decay in peak net current above P_c can be shown to fit the empirical equation

$$I_{net} = \frac{I_0}{1 + \frac{P'}{P_{\frac{1}{2}}}}, \tag{4}$$

where $P_{\frac{1}{2}}$ is the pressure at which the peak net current falls to half of its maximum value, and $P' = P - P_1$ as shown in Fig. 2, where this curve is shown fit to the experimental data.

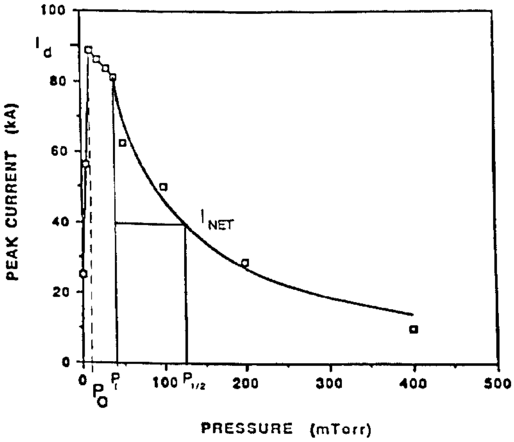

Fig. 2. Effect of gas pressure in the drift tube on the peak injected current, I_{net}.

Table I. Critical pressure P_c for full charge neutralization of the beam computed for various gases (for T = 0.5 MeV beam); and pressure P_0 at which the net current is measured to be the maximum.

Gas	P_c (mTorr)	P_0 (mTorr)
H_2	52	50
He	53	–
N_2	12	–
O_2	10	–
Ar	11	10
CO_2	8	12
Xe	6	10

Current Waveforms

The waveforms of the injected current itself can also given valuable insight about the charge neutralization processes involved in the types of beam-gas interactions described here. Figure 3 shows the evolution of the net injected current with increasing pressure using argon gas. The diode current for these shots was approximately 95 kA. The first waveform, Fig. 3a, was taken with an evacuated drift region. Only a small fraction of the beam is able to enter the drift tube at this point as the beam simply blows apart under the influence of its own space charge field. Figure 3b was obtained at a gas pressure of 5 mTorr of argon ($P < P_c = 11$ mTorr). The current rises approximately linearly as the beam begins to be charge neutralized by the background gas. Here, the charge neutralization fraction, f_e, is such that $f_e < 1$. There is not enough gas in the drift chamber to fully charge neutralize the beam and only a fraction of the beam current is injected into the drift tube. Figure 3c was taken at 10 mTorr, the critical pressure for full charge neutralization. At this point, $f_e = 1$ at the beam tail, and injected current rises to its maximum of the diode current I_d. The entire beam is now injected into the drift tube region. The risetime of the signal is equal to the beam pulse length of 100 ns. Finally, in Fig. 3d, we see the injected current waveform at a pressure (200 mTorr; $P > P_c$) above that required for full charge neutralization. The current rises more quickly than previously (note the increase in slope) as there is a greater amount of background gas available, thus speeding up the charge neutralization process and allowing the beam to propagate into the drift region at a faster rate. However, return currents in the plasma act to cancel the beam, and the current magnitude is reduced from that of the $P = P_c$ case. The waveform then shows a flat top for the duration of the 100 ns beam pulse as the beam continues its attempt to enter the neutral gas region, and the plasma return currents act to cancel it out. After 100 ns, the trace shows a characteristic exponential decay. This arises from dissipation of the field energy into the plasma column, resulting in resistive heating of the plasma. From the decay constant, one can easily obtain the resistivity of the plasma.

Plasma Resistivity

Assuming a uniform, solid plasma column of length ℓ and radius a coaxial to a drift tube of radius b, the inductance of the drift tube and plasma column is

$$L = \frac{\mu_0 \ell}{2\pi}\left(\frac{1}{4} + \ell n \frac{b}{a}\right) \tag{5}$$

where the internal inductance of the beam and the inductance of the coaxial line have been summed together. The resistivity

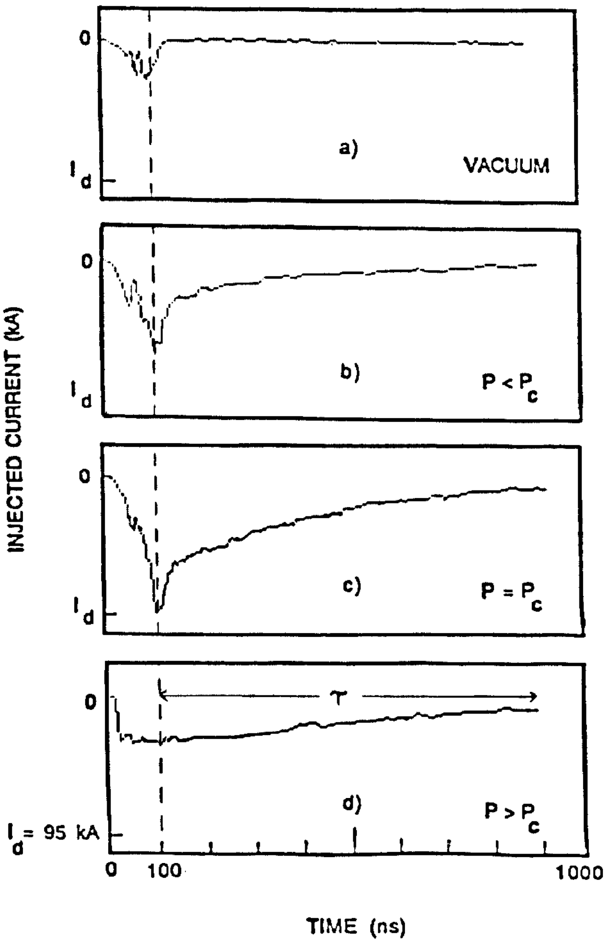

Fig. 3. Evolution of the net injected current with increasing argon gas pressure. a) vacuum drift region, b) $P = 5$ m Torr, c) $P = 10$ mTorr, ($P = P_c$), d) $P = 200$ mTorr.

of the beam is $\eta = R\pi a^2/\ell$, where R is the resistance of the plasma column. Using the measured decay constant $\tau = L/R$ (which is attributed to L/R of the drift tube and plasma column) as shown in Fig. 3, the resistivity of the plasma is then obtained as

$$\eta = \frac{L\pi a^2}{\tau} \qquad (6)$$

Using our beam and drift space parameters of $a = 1.25$ cm, $b = 7.5$ cm, and a measured decay constant of $\tau \approx 1\mu$s, we get a plasma resistivity of $\eta \approx 5$ mΩ cm. In order to bring about a more quantitative background to these results, current work includes determining the time dependent resistivity of this plasma and the dependence of the resistivity on background gas pressure in order to further our understanding of the evolution of the beam-gas interactions and the processes involved.

Summary

A straightforward, qualitative understanding of the charge and current neutralization processes occurring when an IREB is injected into a neutral gas, can be easily gained by a basic analysis of gas pressure effects on the beam and an examination of the current waveforms themselves. By examination of the injected current signal, one can predict the pressure regime ($P < P_c$ or $P > P_c$) in which the beam-gas interactions are taking place. For a given background gas, it is possible to choose the correct neutral gas pressure in order to give full charge neutralization of the beam and maximum injected current. The plasma resistivity can also be obtained from the decay time of the net current waveforms. The time evolution and gas pressure dependence of the plasma resistivity in the drift region is currently being examined.

Acknowledgments

We wish to thank Chris Daniel, Doug Cohen, and J. Pyle for technical support. This work was supported by the Air Force Office of Scientific Research and the U.S. Department of Energy.

References

1. A.C. Kolb, IEEE Trans. Nucl. Sci. NS-22, 956 (1975).
2. C.L. Olson, Phys. Rev. A 11, 288 (1975).
3. F.F. Rieke and W. Prepejchal, Phys. Rev. A 6, 1507 (1972).
4. R.B. Miller, *An Introduction to the Physics of Intense Charge Particle Beams*, Plenum Press, New York, 1982.
5. K. Ono, T. Oomori, and S. Fujita, J. Appl. Phys., 63, 4392 (1988).