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OBSERVED CURRENT ENHANCEMENT WITH
PROPAGATION OF THE ETA ELECTRON BEAM IN AIR

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I. INTRODUCTION

In propagation experiments on the ETA accelerator it has been observed that there is an enhancement of the net current flowing in the direction of the beam current as the beam propagates in gas in an experimental cell. The effect has been observed in different gases including nitrogen, wet and dry air, and neon, and at pressures ranging from 20 Torr to 500 Torr. Previously observed enhancement of the net current has been reported in propagation studies using the ASTRON accelerator and the FX - 25 pulse diode accelerator in the pressure range from 0.1 Torr to 1 Torr in air and nitrogen.¹ This phenomenon was identified as due to a two-stream interaction. Since collisional damping quenches this effect at higher pressures, it is not a likely mechanism for the observed enhancement at high pressure.

One mechanism that can enhance the current significantly at this higher pressure is delta rays. These are energetic secondary electrons produced by the beam in the energy range of 10 keV to 100 keV. They are relatively frictionless and are produced primarily in a transverse direction. They are pushed forward by the beam's magnetic field and become part of the forward current. A Boltzmann code has been developed to study the effects of the delta rays, and results of that code are compared in this report with experimental data.

II. TEST CELL

A test cell for gas propagation studies was fabricated from 14.6 cm ID aluminum pipe to provide a 64 cm long beam path. The gas was confined between

two 0.03 mm thick titanium foils that allowed the beam to pass through at entrance and exit. The cell included various ports for optical and other diagnostics. Principal diagnostics were resistive wall current monitors located just before and after the entrance and exit foils. Another current monitor was located at 39 cm from the entrance foil. The monitors in gas measure the net current, which is the sum of the beam current and any return current induced in the plasma. The monitors in vacuum measure the beam current.

111. COMPARISON OF EXPERIMENTAL RESULTS COMPARED WITH CODE

A typical data set for the current monitors for 100 Torr neon is shown in Fig. 1. The peak injected beam current at entry is 8 kA. The return current partially neutralizes the beam current a few centimeters into the gas. After the beam propagates 39 cm, the peak net current is 12 kA, an increase of 50% above the injected current. Together with the enhanced beam current, there is an associated strong transverse motion of the beam as seen on the x, y traces from the current monitors. As the beam propagates further to 64 cm it becomes quite unstable with large transverse amplitude fluctuations that eventually drive it into the wall.

Figure 2 shows a plot of the peak net current amplitude versus pressure for a beam propagating 64 cm in air. In this case the injected beam current was 7 kA. At pressures below 0.1 Torr there is a region of stable propagation (Ion Focus Regime) with little loss in peak amplitude. In the region between 0.1 and 1 Torr the net current exceeds the injected current. This has been identified to be due to a two-stream interaction and has very strong microwave

Fig. 1. Upper traces show the net currents in 100 Torr of neon; lower traces show the corresponding x and y offsets of the beam from the tank axis.

Fig. 2. Peak net current versus pressure for a beam propagating 64 cm in air.

emission associated with it.² At 1 to 2 Torr, the two-stream interaction is collisionally damped, and strong return currents significantly neutralize the beam current. At these gas pressures the beam propagates well. Above two Torr the net current increases until at 20 to 100 Torr the net current again exceeds the beam current. In this high pressure case, no significant microwave emissions are measured.

An important mechanism causing this enhancement is likely to be delta rays. The gyroradius of the deltas in the strong magnetic field of the beam is small. Hence, the pattern of current flow must be determined by self-consistent treatment of the entire ensemble. In order to model delta ray current enhancement, a numerical code, NUTS, was developed.³ The code solves the full Boltzmann equation for all secondary electrons from 0.1 eV to 100 keV employing a dipole approximation in velocity space. The electron distribution is solved as a function of three independent variables, namely,

$x \equiv ct - z$	the time in the beam frame
r	radial variable
ϵ	electron energy.

The code includes all inertial, non-local, magnetic and electric effects. Atomic collisions are modeled including ionization, avalanche, energy loss, momentum transfer and recombination. The time-dependent electromagnetic fields are calculated self-consistently from the beam current and the evolving plasma currents.

The results of the NUTS code can be compared to the experimental results for a number of key parameters. One experimental result is that the current enhancement is a function of current density. Figure 3 shows a case for which the injected current density was varied by adjusting the focus at entry to the

Fig. 3. Peak net current versus pressure for a beam propagating 39 cm in nitrogen. Injected beam current was the same in both sets of data, but beam size was changed for two different current densities.

gas propagation cell. The higher current density shows increased current enhancement. Results of two NUTS code runs are shown in Fig. 4. They show the same trend to increased delta current as the experimental result, though the magnitude of the delta current is much less than the enhanced net current measured at 64 cm from the entrance foil.

Near injection, the transverse displacements of the beam are small, but there is still current enhancement at higher pressure. The net currents 3 cm from the entrance foil are shown in Fig. 5. At gas pressures of 100, 200, and 500 Torr, the net current in gas clearly increases as the gas pressure is increased and peaks at the tail of the pulse. Figure 6 shows NUTS code results for 76, 200 and 500 Torr. In this case, not only is the trend correct, but the magnitude of the delta current late in the pulse quite closely matches the experimental data. It must be noted that the code modeled beam was 10 kA, whereas the experimental beam was 7.1 kA peak.

Figure 7 shows a radial profile of the net current density as obtained from the NUTS code. The radial current distribution may be divided into three regions:

- (I) Inside the beam.
- (II) Just outside the beam, where the forward delta current continues to enhance the net forward current.
- (III) Where the deltas are reaching the end of their range. They cannot produce significant current, but are very effective in ionizing the gas. In this region a finite E_z then drives a backward plasma current.

A remotely inserted B_θ probe consisting of a single turn loop has been built and installed in the ETA beam propagation cell. Measurements are

Fig. 4. Induced delta currents versus time back from the head of the pulse for two different current densities from NUTS code.

Fig. 5. Measured net current 3 cm from the entry foil for three different pressures. These have

- (1) Repeatable initial conditions with $I_b = 7.1$ kA relatively free of transverse motion.
- (2) Pressure dependence
 - I_{net} (100 Torr) = 6.8 kA
 - I_{net} (200 Torr) = 7.2 kA
 - I_{net} (500 Torr) = 7.6 kA
- (3) I_{net} peaks at beam tail
- (4) $I_{\delta}/I_b \geq 7\%$.

Fig. 6. NUTS results for the buildup of delta ray current at three different pressures.

Fig. 7. Typical delta ray current profile 12 nsec into beam pulse.

currently underway to provide detailed radial current distributions for a number of different gas pressures.

IV. SUMMARY

Current enhancement has been observed with the ETA beam propagating in different gases. There is a characteristic pressure dependence with enhancement observed from 20 to 500 Torr in air, nitrogen and neon. The current enhancement can be a significant fraction of the beam current after it has propagated some distance with 30% to 50% commonly observed. As much as 90% enhancement has been observed with a high current, tightly focused beam. In all cases where sizeable current enhancement occurs, there is a large transverse motion of the beam.

The NUTS code has shown that high energy secondary electrons created by the beam can contribute to the net current as they are pushed forward by the self-magnetic field of the beam. Comparison of code results with experimental results, however, show reasonable correlation with experiment only for a beam that has not propagated. Thus, the delta currents may explain the initial enhancement, but the large current enhancement observed after some distance of propagation is probably due to some other instability mechanism.

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ABSTRACT

It is observed with the ETA electron beam propagating in air that the net current exceeds the beam current for pressures between 20 and 500 Torr. Microwave measurements indicate that this current enhancement is distinctly different than that associated with the two-stream instability at low pressure. Detailed measurements of its dependence on pressure, current, beam size, and propagation distance are given. A theory is proposed that attributes the additional forward current to energetic secondary electrons pushed forward by the beam self-magnetic field. Detailed comparison of measurements with the results of a non-local Boltzmann code are made.

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