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CURRENT ENHANCEMENT UPDATE

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ABSTRACT

Net current enhancement to levels in excess of the beam current has been observed in gases at pressures excess of 50 torr. We delineate the regimes where enhancement is observed. The experimental results fall into two very distinct classes; current enhancement at injection where the beam is only slightly displaced and current enhancement clearly associated with the high amplitude hose instability. A careful theoretical and experimental study of the diagnostics revealed no fundamental flaws although there are several complex and unlikely scenarios which could introduce fictitious current enhancement. Theoretical efforts indicate several mechanisms for generating enhancement but none of the theories can account for the detailed observations.

INTRODUCTION

Current enhancement has been observed (Ref. 1) for beams produced by the ETA propagating in gas at pressures in excess of 50 torr. We have performed additional experiments designed to further document this phenomena with particular emphasis on verification of the diagnostics employed. In this report we discuss the present state of understanding of experimental results, diagnostic limitations, and theoretical predictions.

EXPERIMENTAL RESULTS

Current enhancement observations fall into two very distinct classes. Near the point of injection into gas ($Z < \lambda_\beta$) we often observe a strong enhancement throughout the beam pulse as shown in figure 1. The enhancement is fairly uniform without current spikes. Net currents in excess of the beam current are observed in the 50–500 torr range. With injected currents around 6 kiloamps net currents in gas of 8 kiloamps are recorded. This effect is observed when there is no wire zone present and not observed in the presence of a wire zone. We believe the phenomena depends on the current density and the wire-conditioned beam has a larger equilibrium radius and hence less enhancement.

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The radial location of the enhanced current has been determined using movable B_θ probes. With such probes the net current enclosed within a given radius can be determined assuming the beam is on center. Measurements in figure 2 show there is reasonable agreement between current determined with the beambug and current from the B_θ probe. The enhanced current is flowing very near to the beam channel and not out at large radii. There may be a very slight return current at large radii although the apparent effect is within experimental error.

Current enhancement is also observed downstream of the injection point ($Z > \lambda_\beta$). This enhancement is clearly connected with the high amplitude hose instability which has grown up at this Z location. Here the enhancement is characterized by a spiking of the current. As seen in figure 3 one beambug will display an enhancement for most X in the beam pulse. The next beambug will show the spikes and the following bug will show dramatic current loss. In this pressure and Z regime the beam is undergoing hose motions which are large in comparison with the beam radius but which are small in comparison to the pipe radius. We observe the spiking of the beam current occurs at approximately twice the frequency of the beam hose oscillations indicating an enhancement which is quadratic with beam displacement.

Figure 4 provides an overview of the current enhancement versus pressure and propagation distance for the Spring 1983 beam propagation experiments on ETA. The height of each marker indicates the observed maximum net current. The signature of current enhancement is the same in each picture. Near the point of injection there is some current neutralization which is stronger at lower pressures. As we move further away from the entrance foil the neutralization increases slightly. However, as the beam propagates further the net current starts growing. Growth is faster in Z at the higher pressures. At some critical bug or bugs the net current exceeds the beam current. Beyond this bug the current and charge transported drop dramatically. Hose has disrupted propagation.

In this regime of large amplitude hose we cannot use the B_θ probe to determine the location of the current in radius due to the uncertainities in beam position and lack of repeatability. Thus we cannot specify the location of $J_{net}(r)$.

DIAGNOSTICS

The primary diagnostic for net current measurement is the beambug (Ref. 2). Beam propagation experiments were performed to verify beambug measurements versus other diagnostics. Experiments altering the boundary conditions for return current flow were performed in the beambug test stand. Calculations were performed to study the limitations on beambug measurement due to the finite number of pickoff points.

Experiments concentrated on verifying the beambug measurements against RF loops and B_θ probes. Comparisons of beambug and RF loop measurements revealed no significant differences in the beam current or displacement. B_θ data was also consistent with the net current observations. A further investigation was conducted on the effects of irregularities (ports, gaps) in the return current path. Attempts to distort the return current path produced a fascinating null result.

When major gaps were introduced in the return current path by the use of ports or simply leaving pipes disconnected we could not alter the beambug current reading at the beambug test stand. We were unable to find any flaws in the beambug measurement technique with the other diagnostics we used. Nevertheless, we have constructed a twelve pickup beambug and will construct a Rogowski coil for further experiments when time on ETA becomes available.

Analysis of beambug operations assuming an infinitely long, cylindrically symmetric beam shows the measured current can be enhanced if the beam is significantly displaced; see ref. 2. If the displacement exceeds one half of the pipe radius then errors in excess of 10 percent may occur. However, the position measurements inferred from the beambug difference voltages indicate displacements less than half the pipe radius. Since one typically utilizes the linearized inversion scheme to determine beam location and this is not valid beyond small displacements we developed a full inversion scheme to compute I, X, and Y for a beambug without any small displacement assumptions. We could then artificially construct situations with apparent current enhancement at apparent small displacement. However, when applied to the experimental data the full inversion scheme did not significantly alter the result of the usual inversion process. Measured beam displacements are not sufficiently large to account for observed current enhancements. However, we did not observe displacements in excess of one half the pipe radius yet beam current was getting lost, presumably by scrapeoff on the pipe. Thus the issue of actual beam displacement is not resolved.

A number of scenarios can be constructed with beams which are not infinitely long and cylindrically symmetric. With a four port beambug one could then observe a fictitious enhancement. For example, if a beam bifurcated into two beamlets which each carried one half the current and which approached opposite measurement loops one could measure a current in excess of the beam current and yet a zero deflection. However, it is equally likely that the beamlets would move out at 45 degrees resulting in current depletion. Thus while we cannot preclude one of these scenarios from arising, the possibility is extremely unlikely. Longitudinal bunching would produce current spiking which might appear as some of the hose data does. However, there are bug traces where the enhancement persists for all X whereas bunching would require valleys as well as spikes.

THEORETICAL MODELS OF CURRENT ENHANCEMENT

Several physical effects have been proposed for explaining current enhancement. They will be discussed briefly and referenced in this note.

Delta rays have been investigated extensively by Simon Yu and others (Ref. 3). They find delta rays can lead to current enhancement at injection with nearly appropriate scalings with beam size, current, and pressure. Unfortunately, the magnitude of the predicted effects is on the order of 10 percent while the observations are in the 20-50 percent range. Given the uncertainties involved this topic is worth pursuing further theoretically. It would be most helpful to determine the energies of the particles carrying the excess current.

In the presence of high amplitude hose motion several effects may be important. If the beam breaks sharply it may produce a plasma current in the channel left behind by the beam segment along with the beam current in the new radial location. There are intuitive arguments against this possibility but a more detailed calculation of the induced currents would be useful. A fieldsolver capable of handling large amplitude beam displacements is required to solve this problem. We have implemented a version of the DYNASTY code (Ref. 4) at LLNL and will investigate the consequences of large amplitude hose on net current.

Ed Lee has pointed out that in the presence of high amplitude hose the beam has a significant transverse momentum. To conserve energy the beam must have lost momentum in the forward direction. If this momentum appears in the less massive (by a factor of γ) plasma electrons then a gain in current will occur. However, calculations show any excess momentum in the plasma electrons will be removed very quickly by collisions with the background gas. Unless the electrons acting as the momentum sink for the beam are also collisionless this mechanism cannot account for the observed current enhancement.

Finally, a careful study of the data suggests the current enhancement is often associated at least partially with bunching. A beam segment which is undergoing large amplitude hose motion in the transverse direction will have its Z directed beta reduced and will bunch against the subsequent beam segments if their hose amplitude is lower. This mechanism can explain local current enhancement in X with spiking but not the global enhancement which is usually seen near the onset of high amplitude hose.

SUMMARY AND COMMENTARY

Observations of current enhancement in the 50-500 torr range in ETA gas propagation experiments are still not understood. There are distinct regimes with the phenomena in the absence of or presence of high amplitude hose. More detailed B_θ measurements indicate the current flow pattern is near to the beam current pattern in radius (there are no large forward or return current flows well outside the beam radius).

Further experimental work is required to verify the present diagnostics. The comparison of the twelve port beambug and the Rogowski coil is required. Determination of the energy of the current carriers would be of high value.

The full significance of the current enhancement phenomena hinges on the connection between enhancement and high amplitude hose. Since beams undergoing high amplitude hose motion are not of programmatic interest it follows that if current enhancement is strictly a high amplitude hose phenomena its study is of low priority. Upcoming experiments on ATA with conditioned, well characterized beams with low amplitude initial perturbations will be pivotal in determining the significance of current enhancement.

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4. B. Hui and M. Lampe, NRL Memorandum Report 5138, NRL, July 27, 1983.

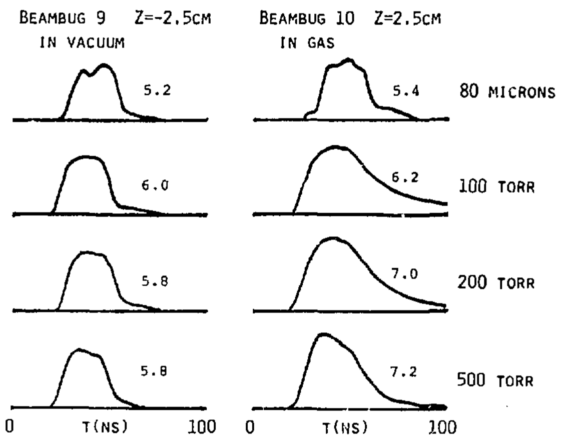

Figure 1. Current enhancement at injection into gas for several pressures.

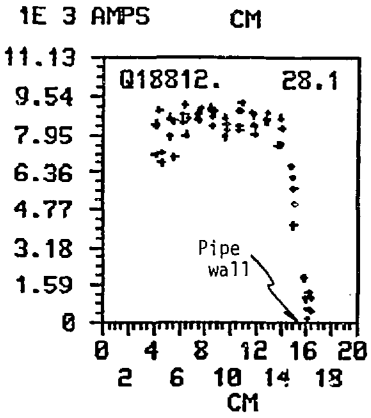

Figure 2. Radial net current enclosed versus probe position, p=500 torr.

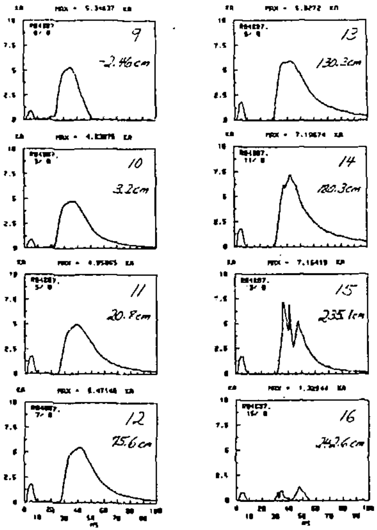

Figure 3. Current enhancement versus Z for hose unstable beam, 100 torr.

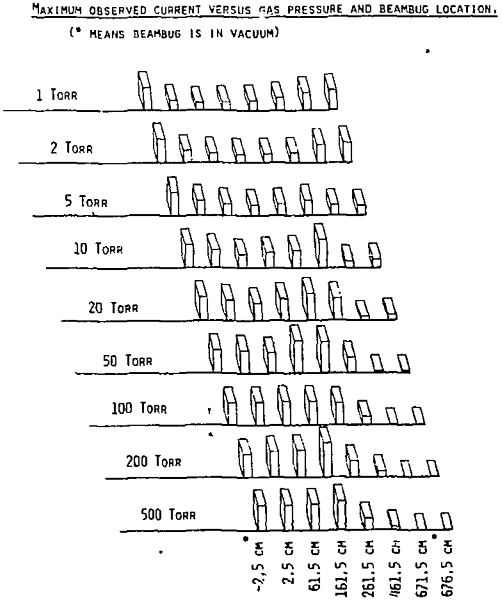

Figure 4. Maximum net current vs. pressure and bug Z location.