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NEUTRALIZATION OF POSITIVE PARTICLE BEAMS BY ELECTRON TRAPPING*

R. M. Mobley, A. A. Irani, J. L. LeMaire,** and A. W. Maschke
Brookhaven National Laboratory
Upton, New York 11973

I. Introduction

The Heavy Ion Fusion (HIF) group at Brookhaven plans a series of experimental tests of positive beam neutralization. Present concepts of pellet fusion using heavy ion beams envision beam parameters something like those in Table I.

TABLE I

8 beams of 30 GeV U^{6+}

6000 amperes/beam for 4 nsec

Beam power 240 x 10^{12} watts

Energy .96 megajoules

Spot size at pellet 0.1 cm^2

Problem areas in which space-charge neutralization will be extremely useful or indispensable include:

1. Final focus region--a 5 to 10 meter drift region where the beams are focused from a diameter of several centimeters to a fraction of a centimeter.

2. Final bunching--a 100 to 1000 meter region in which the final stages of bunching from several tens of amperes intensity to kiloampere levels occur.

3. Low β acceleration--a conventional accelerator problem area in which the space-charge limits beam brightness.

We are using a 750 keV Cockcroft-Walton preaccelerator with a duoplasmatron source to test various neutralization techniques. The source can deliver ~200 mA of H^+ and ~20 mA of Xe^+ for 500 μsec or longer at 5 pulses/sec.

FIG. 1. APPARATUS

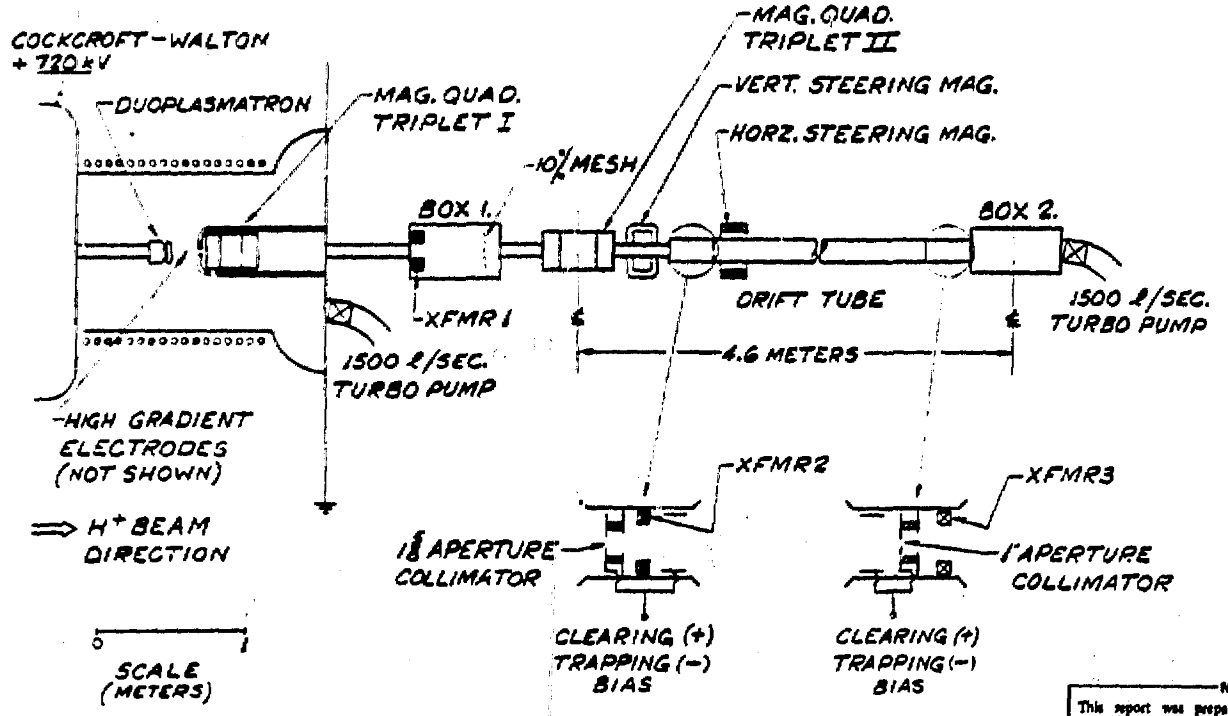

Fig. 1 The drift tube diameter is 6 in. The smaller pipes are 3 in. diameter. Vacuum components are nearly all aluminum.

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This report gives experimental results of transverse space charge studies of a 720 keV, 60 mA H^+ beam in a drift region of 4.6 meters. The beam diameter was ~2 to ~5 cm, depending on intensity and degree of neutralization.

II. Experimental Set Up

The apparatus is shown in Fig. 1. The beam optics were adjusted, and the collimator sizes chosen (in a sequence of steps to be described), with the object being to provide a best-focus condition at Box 2. The best-focus condition was obtained with a low-intensity sample of the beam using a 10% mesh in Box 1. This beam, < 10 mA, has negligible space-charge blow-up.

The sequence of steps was:

1. Calculate currents and set quad Triplet II to focus a parallel beam at Box 2.

2. Choose upstream beam defining collimator of 1 5/8 inches to match beam diameter filling Triplet II aperture.

3. Adjust source and Triplet I to get brightest spot on fluorescent screen in Box 2. Make visual observation of full beam (10% mesh removed) spot size to get estimate of space-charge size change.

4. Choose 1 inch aperture downstream collimator to pass low intensity beam, and to intercept a good fraction of the high intensity beam.

5. Adjust steering magnets for maximum current to Faraday cup.

6. Retune quad Triplet II slightly.

In practise, the above steps were done several times in different orders, but we soon arrived at source, quadrupole, and steering settings used throughout the experiment.

The upstream and downstream collimators were biased to serve as clearing-trapping electrodes for electrons. Inner sleeves of Al, insulated from the 5 inch vacuum pipe, were originally intended to serve this purpose. They were externaly connected to supplement the collimators, as shown in the details of Fig. 1.

The Faraday cup is a 1/8 inch thick aluminum plate of 3 x 4 in.^{2}. The plate is surrounded by an open-sided aluminum box which is wrapped with a tungsten wire grid. The box and grid are biased to -400 V to suppress secondary electrons leaving the Faraday cup surface, and to exclude electrons and collect positive ions from the background. With H^+ at 720 kV, we find that with no bias the cup gives 20 to 50% higher signal levels, depending on the background vacuum condition, apparently due to vacuum surface layer effects.

III. Experimental Results

Visual observations had shown a bright beam spot of 3/4 to 1 inch diameter, with a halo filling a temporary 2 1/2 inch aperture. The spot grew larger with higher intensity, and when +300 V bias was applied to the clearing electrodes. These observations were confirmed with Faraday cup measurements of beam transmitted through the 1 inch downstream aperture.

The results are shown in Figs. 2-5. The upper trace is the beam current monitored by transformer 1 (120 to 140 mA). The lower traces are Faraday cup currents at 20 mA/div. Figures 2 and 3 show transmitted currents of 50 mA and 15 mA, respectively, corresponding to -300 V and +300 V biases on the clearing-trapping electrodes. Even with electrodes at ground potential, Fig. 4 shows that

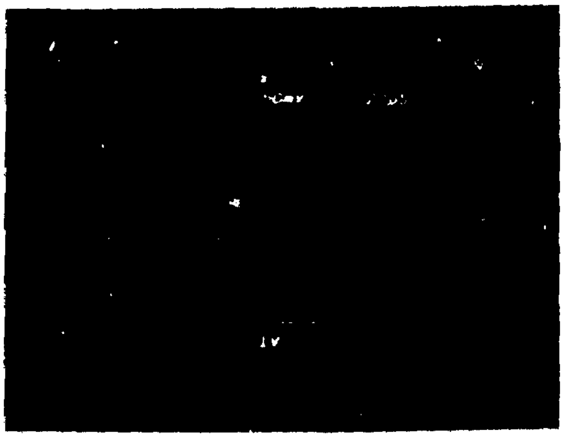

Fig. 2 Upper trace, beam monitor (transformer 1) at 100 mA/div. Lower trace, Faraday cup current at Box 2 at 20 mA/div. The electrodes are biased -300 V. Result is same from +20 → -300 V

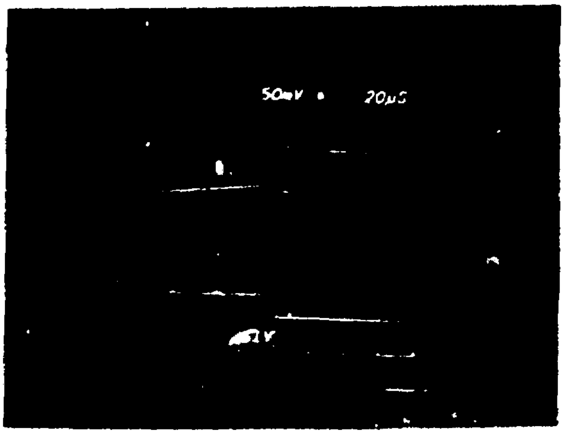

Fig. 3 Upper trace, beam monitor (transformer 1) at 100 mA/div. Lower trace, Faraday cup current at Box 2 at 20 mA/div. The electrodes are biased +300 V.

neutralization occurs. Above +240 V clearing potential, little further de-neutralization occurs, as shown in Fig. 4.

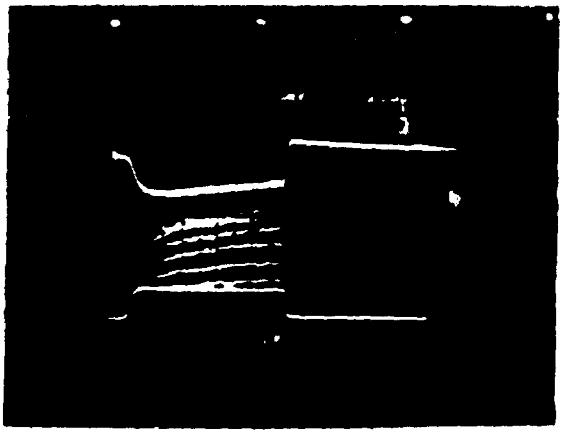

Fig. 4 Multiple exposure. Electrode bias varied from 0 - +320 V in 40 V steps. No further decrease in transmission above +240 V.

Figure 5 shows that for the 10% beam, there is no change in transmission when the clearing electrode polarity is switched.

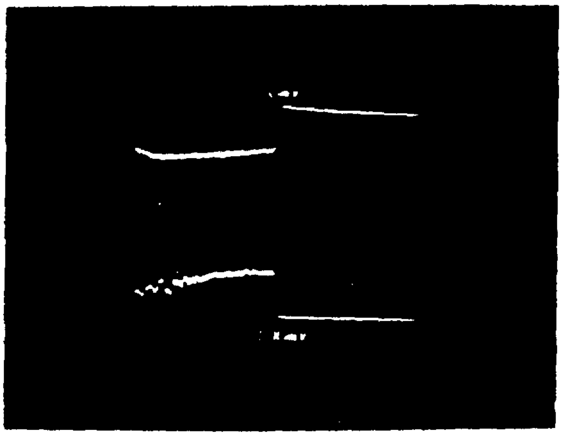

Fig. 5 Double exposure, to show that the 10% beam has same transmission with + or -300 V electrode bias. The current is 5 mA/div.

The rise time of the beam current signal is due to the rise time of the source. We applied a +130 V square pulse to the clearing electrodes, falling to ground when the beam had stabilized, and observed that the transmission (therefore the neutralization) changes level within 1 μsec. This is shown in Fig. 6.

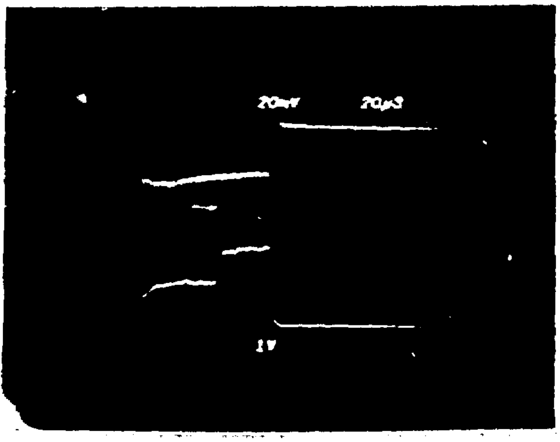

Fig. 6 A square wave voltage of +130 V is applied to the electrodes at t = 0, and removed at t ≈ 60 μsec. The beam transmission increases in ~1 μsec.

We conclude that the beam is rapidly self-neutralizing. Furthermore, since increasing the clearing bias above +240 V has no effect (we went as high as 1 kV) we think that the electron removal is nearly complete.

IV. Discussion of Results

The change in H^+ beam transmission that we obtain with this particular geometry is short of a fundamental result. From an accelerator applications point of view, we would like to know the limiting beam brightness (the quantity intensity/transverse emittance)^2) we can obtain with neutralization. From a beam propagation theory viewpoint, we need to know the source of the neutralization electrons, properties of the potential well of the H^+ beam, properties of the background plasma, and the degree of neutralization achieved. However, at this stage we can make two important conclusions described in A and B below.

A. The change in transmission observed is consistent with complete neutralization in the drift pipe for grounded or negative electrodes, and with complete de-neutralization in the case of > +240 V electrodes. The space charge calculation of the beam blow up goes as follows: A zero-current optics calculation yields a 1 in. diameter spot size at 4.6 meters for a beam of ϵ = emittance/π = 7 x 10^{-6} meter-radians, with a 2 in. effective aperture at the focal plane of Triplet II. Assuming a uniform charge distribution in x-y space the focal spot vs. current with space-charge forces is as shown in Table II.

TABLE II

Current (mA)	Spot Radius (cm)
1	1.27
10	1.54
20	1.88
30	2.25
40	2.61
50	2.97
60	3.32

The ratio of the spot area at 60 mA from Table II to the 1 in. aperture is 6.8. We observe transmitted current ratios of 3 to 4. If we choose a smaller ϵ (say, that corresponding to a 3/4 in. spot), we can obtain agreement with the experiment. It is misleading to make that kind of fit, however, since our assumption of a uniform xy distribution is probably not valid. Hence, we say that our results are consistent with 100% neutralization, but we have not demonstrated neutralization to that degree.

B. Background gas ionization cannot be the main source of the electrons. The neutralization time of 1 μsec from Fig. 6 cannot be produced with the largest estimates of the ionization cross section, and the most optimistic assumption about electron trapping in the potential well of the beam. Moreover, measurements of the current to the electrodes in the clearing mode, allowing for positive beam cancellation (including secondary electron emission), yield ~100 mA of electron current. That corresponds to more than one electron per primary proton in the steady state.

A rough estimate of the background ionization goes as follows: An H^+ beam of 60 mA form a potential well for electrons. For a 1 in. (radius) beam in a 3 in. (radius) pipe the potential is -150 V at r = 0, -100 V at r = 1 in., and 0 V at r = 3 in.

Differential cross sections for the reaction:

$$H^+ \text{ (750 keV)} + H \rightarrow H^+ + H^+ + e,$$

from Bates and Griffing[1] show that collisions yielding electrons above 50 eV have a negligible contribution to the cross section. Taking the H_2 cross section to be a factor of 2 higher, we get $\sigma_T < 5 \times 10^{-17}$ cm².

The background density at 10^{-4} Torr is $n_b = .35 \times 10^{13}/\text{cm}^3$. (Ion gauges in Box 1 and Box 2 give background pressure readings of 1.2 and 1.8×10^{-6} Torr, respectively. The ion gauge correction factor for H_2 is 2.2, giving approximately 4×10^{-6} Torr if the background is H_2. If the background is assumed to be air, there is no gauge correction, but the cross sections should be $A^{2/3} \approx 4$ times higher.)

Taking 10^{-4} Torr as an upper limit the mean collisional length ℓ_c is:

$$\ell_c = \frac{1}{\sigma_T\, n_b} = 57 \text{ meters.}$$

Assuming that all of the electrons are trapped in the potential well, each proton has a .08 probability of creating a trapped electron. Thus, it would take ~12 protons to produce 1 electron in the pipe, or 12 proton transit times to produce 100% neutralization. Since the proton velocity is 12 m/μsec, the transit time for 4.6 m is .38 μsec. This gives 4.6 μsec for neutralization. In this linear model, it would take 2.3 μsec to reach 50% neutralization.

A detailed calculation allowing for the collapse of the potential well as neutralization proceeds, and integrating the differential form of the cross section, yields longer times as shown in Fig. 7.

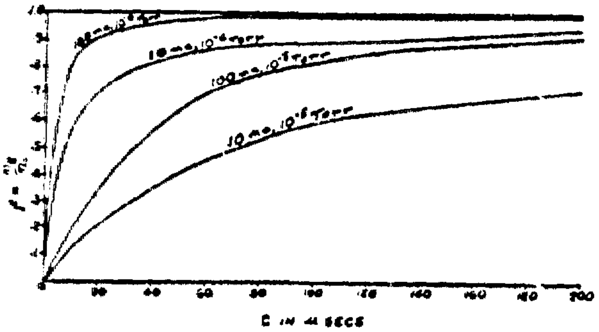

Fig. 7 f is the calculated degree of neutralization vs. time. As neutralization proceeds, the potential well is depleted in this model.

The question remains, how are the neutralizing electrons produced? Further measurements of the rise time are in progress to help resolve this question. Three inch collars have been placed in the beam pipe to prevent grazing of the drift pipe wall, which should reduce secondary electron production to .2 - .5/proton. The vacuum can be improved. In addition, we have not fully considered what the H_2^+ component of the beam contributes to the process.

V. Acknowledgments

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References

1. D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London), A66, 961 (1953).