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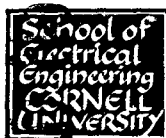


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FROM

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A. S. Gilmour, Jr.
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20 October 1962



LINEAR BEAM MICROWAVE TUBES, Technical Report No. 22

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School of Electrical Engineering
CORNELL UNIVERSITY
Ithaca, New York

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ION EFFECTS IN A BRILLOUIN BEAM

A. S. Gilmour, Jr. and D. D. Hallock

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CONTENTS

	Page
I. INTRODUCTION	1
II. QUALITATIVE TREATMENT OF ION FORMATION	2
III. OBSERVATIONS ON THE BRILLOUIN BEAM	5
A. Description of the Beam Analyzer	5
B. Ion Effects Observed in the Beam	8
IV. CONCLUSIONS	15
V. REFERENCES	17

ABSTRACT

This report describes some of the effects of ion neutralization of the space charge in a Brillouin beam noted while making d-c and r-f current measurements with an electron beam analyzer. Ion neutralization made the beam behavior depart from the ideal Brillouin behavior, resulting in a difference between theory and experiment. As ion neutralization was reduced, the experimental observations approached the theoretical predictions more closely. Ion neutralization was observed by injecting gas into the beam analyzer, on which the measurements were made, and observing the change in beam shape by measuring the current density at various points in the beam on an oscilloscope and an x-y recorder. The beam shape changed during the cathode pulse, indicating a build-up of ions, the rate of ion formation being a linear function of time during the pulse and varying with pressure. The presence and formation of ions in the beam seemed to increase the degree of nonlaminarity of flow.

I. INTRODUCTION

In the course of the investigations of the electron flow in Brillouin beams described in other Cornell University research reports¹⁻³ the effect of ion neutralization of the space charge in the beam was observed. The purpose of this report is to present these observations in a useful and meaningful form. Ion neutralization made the beam behavior depart from the ideal laminar behavior, on which r-f theories are based. This difference between the theoretical predictions and experiment was not, in fact, due to a deficiency in the theory; for as ion neutralization was reduced, the experimental observations approached the theoretical predictions more closely.

The simple, qualitative treatment given by Harman⁴ of the production of ions by the electron beam was used to predict the degree of ion neutralization in the beam and was shown to be valid.

Cutler and Saloom⁵ reported that the creation of positive ions in the beam caused the current density on the beam axis to increase during the pulses and caused the beam edge to move inward toward the axis. Section III describes similar effects of ion neutralization on the beam shape observed in this experiment. The effect on the "tails" of the beam of varying the pressure in the gun is also shown.

II. QUALITATIVE TREATMENT OF ION FORMATION

The effect of ionization of the residual gas in a vacuum tube on the beam behavior is not treated exactly because of the large number of variables involved. Some values can be obtained from equations given by Harman,⁴ which predict the magnitude of the ion effects, and this was done for the beam analyzer used at Cornell University. There were certain limitations imposed by the experiments, which rendered an exact analysis of the ionization problem impossible. The most serious of these was that the composition of the gas in the analyzer was not known; in fact it was not even known whether the composition remained constant while the analyzer was in operation and the control rods were being moved in and out of the drift region.

From Harman's⁴ equations (5.72) and (5.73), we have for the electron density,

$$\text{electrons /cm}^3 = 3.7 \times 10^9, \quad (1)$$

for the beam parameters used in this experiment; and for the gas molecule density,

$$\text{molecules /cm}^3 = 6.4 \times 10^9, \quad (2)$$

for a pressure of 2×10^{-7} mm Hg. This shows that these two densities were comparable in this experiment.

The densities of gas molecules and electrons were not as high as the numbers might indicate, for the mean free path of an electron in the analyzer was of the order of 10^3 meters. The calculation of the mean-free path was based on the assumption that the residual gas was largely oxygen, carbon monoxide, and nitrogen. These have been shown to be prominent among the

residual gases in many vacuum tubes. The importance of this estimate of the mean-free path is that it is much greater than the cathode-to-collector spacing in the analyzer, so that most of the electrons did not suffer collisions with gas molecules in transit. Even when a collision did take place, the probability of ion formation was rather small, probably of the order of one-third to one-tenth of the collisions producing an ionized molecule. Those ions formed were primarily positive ions resulting from an outer shell electron being separated from the atom.

As a result of the long mean-free path and the low probability of ionization, the rate of ion production in the analyzer was much smaller than the rate of electron production. The ion density could become comparable to the electron density, however, because the ions remained relatively fixed in position. Harman gives as a typical experimentally determined rate of positive ion production for an unspecified gas:

$$\text{ions/second/cm of beam} \approx \frac{PI}{V} \times 10^{23}, \quad (3)$$

where P is the pressure in millimeters of mercury, I is the beam current in amperes, and V is the beam voltage in volts. From this equation and the cross section and area of the beam near Brillouin flow, the ion density can be determined. The values calculated are given in Table I.

Table I.
Calculated Values of Ion Density as Function of Time

Time after start of beam pulse (μsec)	1	10	100
Ion density (ions/cm ³)	1×10^7	1×10^8	1×10^9

This shows that after 1 μ sec the ion density in the beam was a negligible fraction of the electron density; after 10 μ sec the ion density had reached a level at which it could begin to affect the charge density in the beam (and hence the beam shape). This is in agreement with the results reported in the next section. After 100 μ sec the ion density shown in Table I was very nearly the electron density shown in Equation (1). Equation (3), from which Table I was derived, does not allow for the removal of ions from the beam region. In fact, a saturation level would be reached beyond which the charge density (or ion density) in the beam would not change.

If zero initial velocity is assumed, simple calculations show that between pulses the ions formed in the beam region diffused to the walls of the drift tube. When the electron charge was removed at the end of the pulse, a collection of positive ions remained in the center of the drift tube. The space-charge forces of the ions caused them to move quickly out of the beam region toward the wall of the drift tube, where they recombined.

III. OBSERVATIONS ON THE BRILLOUIN BEAM

A. Description of the Beam Analyzer

The beam analyzer with which the ion neutralization in the Brillouin beam was observed has been described in great detail in other reports.^{1, 3, 6} For an understanding of some of the observations reported here, however, it is necessary to have an understanding of the operation of the beam analyzer and the vacuum system.

A simplified sketch of the beam analyzer is shown in Figure 1. The electron gun* used for this experiment was a shielded Pierce-type gun of perveance 1.15×10^{-6} , which was operated at 5,000 volts. Because of the low average power that could be dissipated by the beam-collecting apparatus, the gun was pulsed at a repetition rate of 60 cps with pulse lengths of 10 - 30 μ sec. The ball valve served to isolate the electron gun from the drift tube, so that the drift tube could be opened to allow for changes in its internal structure without contaminating the oxide cathode of the electron gun. The beam was collected on a movable beam scanner in the drift tube. The collecting plate on this scanner was carbonized to reduce the emission of secondary electrons. A small fraction of the beam passed through a pin-hole in the collecting plate and was collected at a Faraday cage. By moving the scanner transversely and axially in the drift tube, one could measure the current density at any point in the beam.

The vacuum system of the beam analyzer is shown in Figure 2. The drift tube was the major part of the primary vacuum system. This system was originally pumped with a 20-l/sec diffusion pump, but this was replaced

* This gun was obtained from a Sperry STL-100, one of five donated to the School of Electrical Engineering by the Sperry Gyroscope Company.

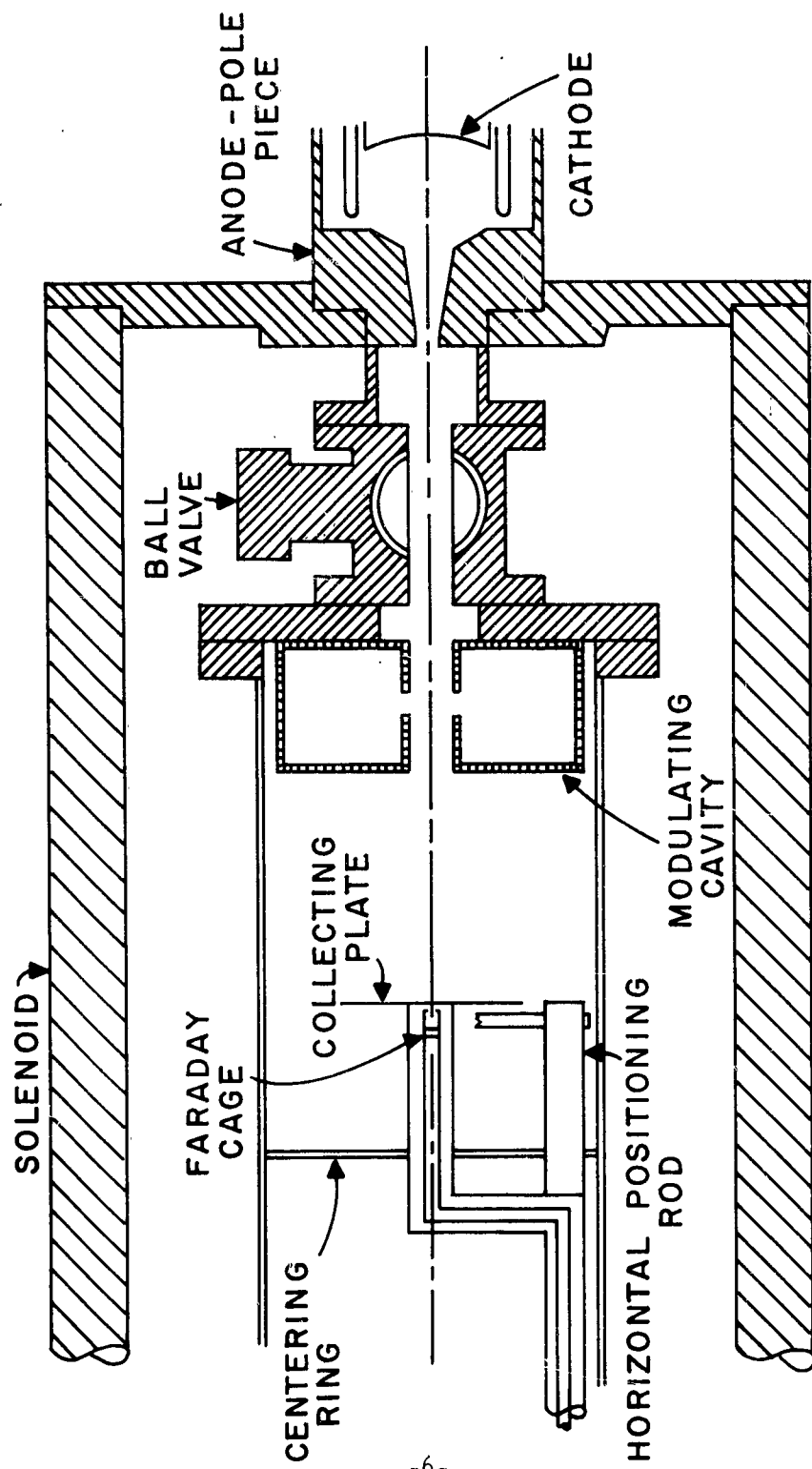


Figure 1. Simplified Sketch of Beam Analyzer.

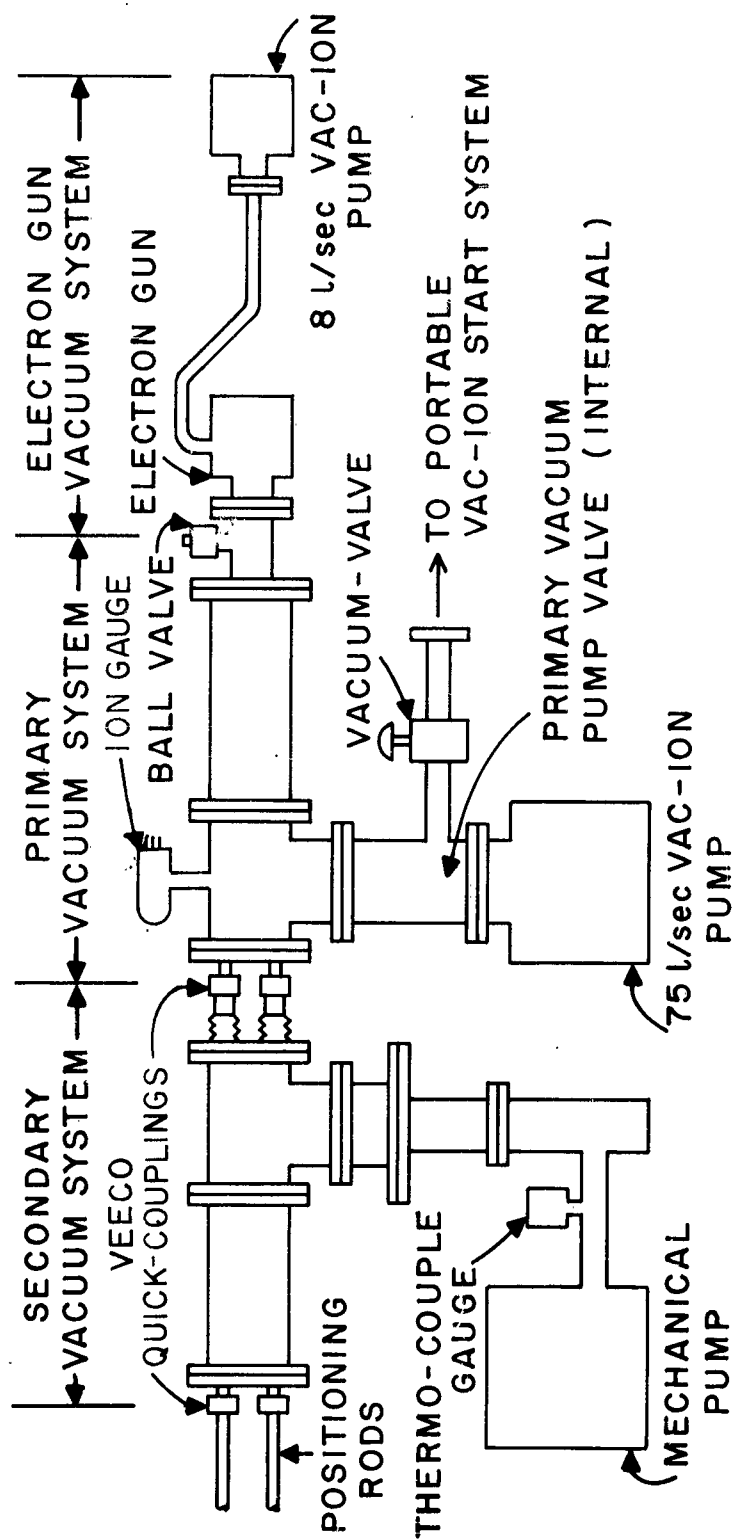


Figure 2. Vacuum System of Beam Analyzer.

with the 75-1/sec VacIon pump shown in the figure to obtain a greater pumping speed and to avoid oil contamination of the internal structure and oxide cathode. Provision was made for independent pumping of the electron gun with an 8-1/sec VacIon pump when the ball valve was closed. The secondary vacuum system served to keep the positioning rods that controlled the beam scanner at a pressure of about 10 microns of atmospheric pressure so that the pressure rise in the primary vacuum system was kept at a minimum when the positioning rods were pushed into the drift tube. The vacuum seals for the positioning rods were sliding O-ring seals.* An ion gauge was attached to the analyzer for measuring the pressure when the primary system was pumped by the oil diffusion pump.

B. Ion Effects Observed in the Beam

The effects of ions were observed when an oscilloscope was used to monitor the electron current arriving at the Faraday cage from the sampling aperture in the beam-collecting plate. Shown in Figure 3 are oscillograms of the cage current at the center of the beam before and after gas was injected into the analyzer (the gas was injected by moving the beam-measuring apparatus rapidly into the analyzer). The oscillogram in Figure 3a was obtained before injecting the gas with the pressure in the analyzer at 2×10^{-7} mm Hg, as indicated by the ion gauge. Immediately after the gas was injected, the pressure indicated by the ion gauge increased to 4×10^{-7} mm Hg and the oscilloscope pattern shown in Figure 3b was obtained. During the succeeding period of about 10 sec, however, while

* Manufactured by Vacuum Electronics Company

the pressure decreased to 2×10^{-7} mm Hg, this pattern changed and returned to that shown in Figure 3a. Shown in Figure 4 are similar oscillograms of the cage current near the edge of the electron beam before and after gas was injected into the analyzer.

Figures 3 and 4 show that the leading edges of the pulses all have the same amplitude and the amplitude of the trailing edge increases at the center of the beam and decreases at the edge of the beam. By plotting the amplitudes of the currents at the leading and trailing edges of the pulse as the sampling aperture was moved horizontally through the beam at the vertical center position of the beam, we obtained the data for the curves shown in Figure 5. These curves clearly show that ions build up in the beam during the pulse and that the ions partially neutralize the negative space charge of the electron beam. Since the magnetic forces tending to compress the beam then become larger than the electrostatic forces that cause the beam to diverge, the diameter of the beam decreases and the density of current at the beam center increases. The nearly linear rate of ion formation indicated by the increase and decrease of current densities in Figures 3 and 4 further substantiates the applicability of Equation (3) during the pulse.

The data used to measure the d-c and velocity-modulated beam was taken by measuring the average current to the Faraday cage as a function of position in the beam. Since an average was used, the effect of ion neutralization was to make the observed beam cross section appear as an average between Figures 5a and 5b. Typical beam cross sections that illustrate this are shown in Figure 6.

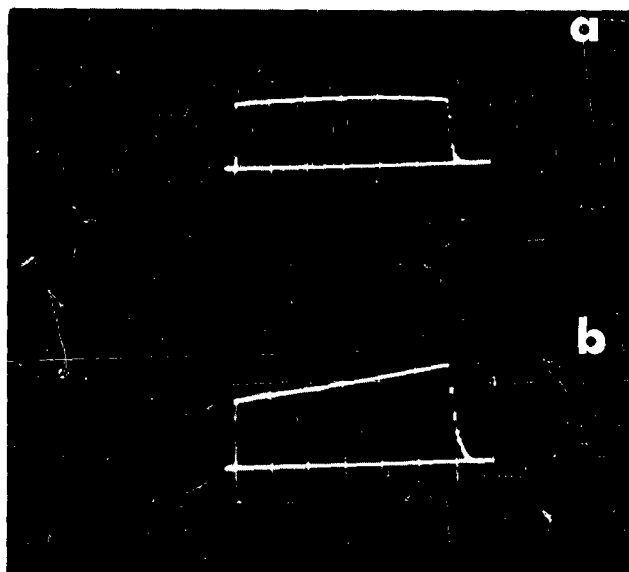


Figure 3. Oscillograms of Current Collected by Faraday Cage at Center of Beam: (a) before Inserting Gas and (b) after Inserting Gas.

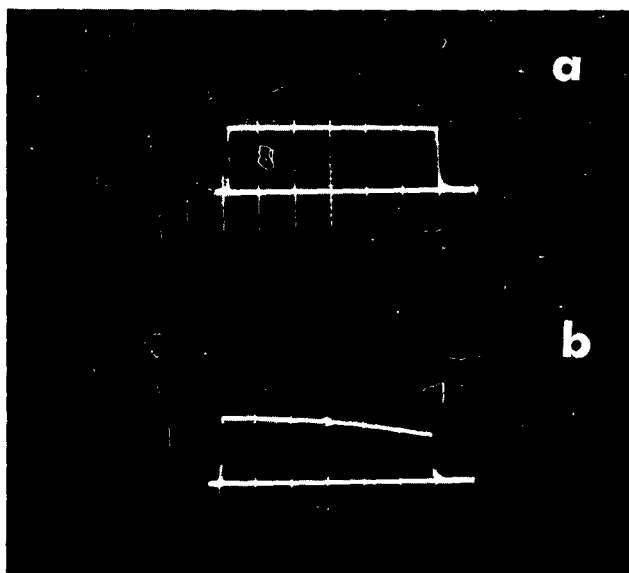


Figure 4. Oscillograms of Current Collected by Faraday Cage at Edge of Beam: (a) before Inserting Gas and (b) after Inserting Gas.

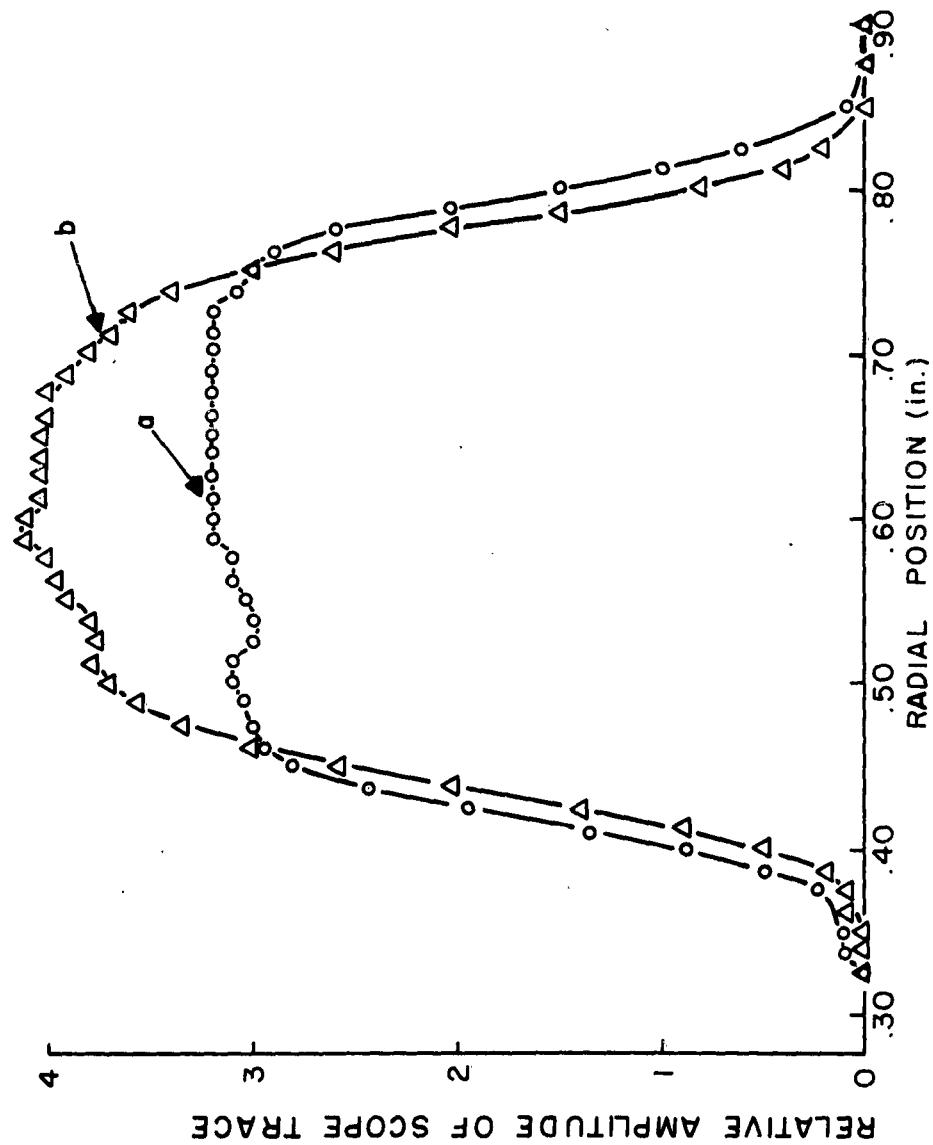


Figure 5. Beam Current Density as a Function of Radial Position of the Sampling Aperture for 30- μ sec Pulse: (a) Data from Beginning of Pulse (b) Data from End of Pulse.

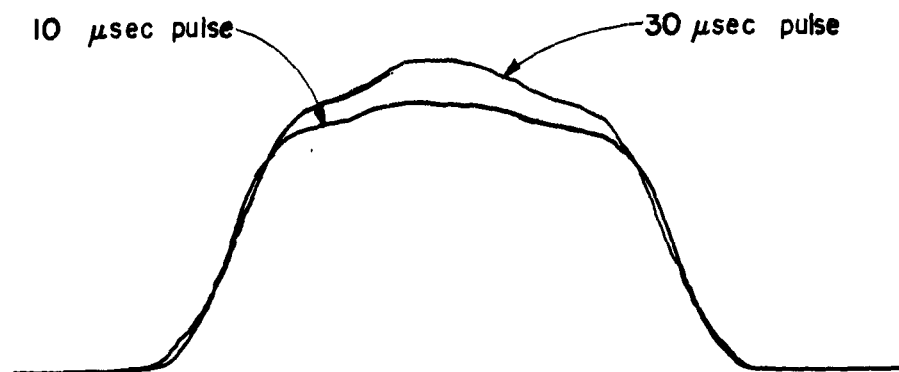


Figure 6. Beam Cross Sections Showing Effects of Ion Neutralization for (a) 30-μsec Pulse and (b) 10-μsec Pulse.

After the results shown in Figure 6 had been obtained, it was noted that there was a region in the electron beam in which some ion neutralization was present, even at indicated pressures below 2×10^{-7} mm Hg, when no gas was being injected into the analyzer. The oscilloscope pattern of the Faraday cage current at the beam center was similar to that shown in Figure 3b at all times. The injection of gas into the analyzer simply increased the slope of the top of the pulse.

This region was the 2 - 4 in. of the drift tube after the beam left the modulating cavity shown in Figure 1, the longer distance occurring when the pressure in the analyzer was the highest. It was concluded that the primary cause of this neutralization was that the drift region through the ball valve and the gun were inadequately pumped when the scanner was positioned close to the modulating cavity. As a result there was a pressure rise in this region, which resulted in a higher degree of ion neutrali-

zation of the beam. This was not indicated by the ion gauge because of its position in the analyzer (see Figure 2).

Because of the ion neutralization in this region resulting from the reduced pumping speed, it was desirable that the pressure indicated at the ion gauge be lower than 2×10^{-7} mm Hg, so that the pressure in the ball valve would not rise above this limit. An improvement in the analyzer performance in this respect was obtained by installing a 75-l/sec VacIon pump as the primary vacuum pump. When this was done it was possible to reduce the indicated pressure to the low 10^{-8} mm Hg range; consequently the degree of ion neutralization was reduced correspondingly when the scanner was within three inches of the modulating cavity.

The electron beam was observed to have low density "tails" surrounding it. The electrons in the tails of the beam used in this experiment had an axial velocity distribution of 95 - 100 per cent of beam velocity.¹ By observing the "tails" of the electron beam both with an oscilloscope and an x-y recorder, it was noted that the amount of current in the tails depended upon the pressure in the electron gun as indicated by the ion pump attached to the gun. It is apparent therefore, that some of the electrons in the "tails" must have originated from the ionization of gas molecules in the electron gun near the cathode. These electrons were accelerated through a large fraction of the beam potential and therefore had the velocity distribution of 95 - 100 per cent of beam velocity, as indicated.

IV. CONCLUSIONS

The effect of ion neutralization of the space charge in a Brillouin beam was noted. It was shown that even under pulsed conditions at what are considered to be high vacuum levels this effect can produce a noticeable change in the beam shape. It was also shown that rather small pressure changes in this high-vacuum region near the critical point, where ion neutralization becomes important, can noticeably affect the beam cross section. Thus with a reduction in pressure of an order of magnitude, ion neutralization will have a negligible effect on the focusing of the beam when this reduction is made in the appropriate range of pressures. The approximate relations given by Harman and simple calculations were shown to be useful in predicting the appropriate range of pressures for a given set of beam parameters. Because of the approximately linear rate of increase of ion formation with time during the pulse, a change in pulse length of an order of magnitude was shown to be equivalent, in terms of the degree of ion neutralization at the end of the pulse, to a change in pressure of an order of magnitude. It was shown that allowances for changes in the effective pumping speed might be necessary when structures are moved inside the vacuum system.

The electrons that appear in the beam "tails" execute radial motion of large amplitude and are therefore nonlaminar. The increase in the current amplitude of the beam tails with increased ion concentration indicates that increasing the formation of positive ions by the electron beam produces some nonlaminarities.

For the beam used in these experiments with a current density of about 2.5 amperes/cm², the upper limit for pressure is about 1×10^{-7} mm Hg, if ion neutralization of space charge is not to disturb the beam focusing seriously.

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