AIAA ELECTRIC PROPULSION CONFERENCE

BROADMOOR HOTEL, COLORADO SPRINGS, COLO. MARCH 11-13, 1963

63-021

SOME PROBE EXPERIMENTS ON A HIGH ENERGY CESIUM ION BEAM *

by

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*The work reported herein was partially supported by the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-948.

ABSTRACT

A probe has been developed which is, in effect, a directional Langmuir probe. The directional quality is necessary for use in a beam of high energy ions to eliminate the effects of the streaming ions on the probe operation. This probe has been utilized to measure the back-streaming (albedo) electron component to verify the bottle model of space-charge neutralization. It has also been possible to infer the density of slow ions in the beam created by gas ionization and to infer a value of the cross section for such gas ionization which agrees with the anticipated value.

INTRODUCTION

While ion neutralization is no longer generally considered a thorny problem with electric propulsion devices, it is incompletely understood at best. Theoretical analyses are abundant but always contain unrealistic simplifying assumptions and can only be useful in providing leads for experiments which may yield more definitive information.

Early neutralization experiments revealed a curious phenomenon. When the beam was shown to be neutralized by inducing current in a coaxial hoop, simultaneous Langmuir probe measurements indicated that high energy electrons were present in the beam in sufficient density that a net negative current should be flowing. A hypothesis — the so-called "bottle model" — was offered to explain this seeming contradiction. This hypothesis pictures the ion beam as a bottle in which the electrons are trapped by reflection at the boundary of the beam where an electron sheath is predicted. Reflection from the end of the beam reverses the direction of travel of electrons thus causing a flux of electrons back toward the engine. However, a net drift of electrons away from the engine was supposed which had such velocity and density that the net electron current equalled the ion current. It was for the observation of these albedo electrons that the window probe was conceived. They have, in fact, been observed and are of the order of magnitude predicted by the theory.

Because of the ability of the window probe to operate within the ion beam and yet not respond to the high energy ions, it has also been possible to observe the slow ions created by interactions of the high energy cesium ions with the residual gas atoms in the vacuum chamber. From these data we have calculated a cross section of 4×10^{-17} cm^2 for the residual gas which is in rough agreement with the value anticipated from similar data for neon and argon. The effects on ground simulation studies of the high density of slow ions may be very important since the density is of the same order of magnitude as that of the high energy ions themselves. Thus, the potential distribution which would normally exist within the beam may be severely altered by their presence.

The above-mentionedground simulation studies are being conducted at Hughes Research Laboratories under a contract from the Arnold Flight Test Center. These studies include experiments designed to demonstrate that ion engines will perform adequately in space.

DESCRIPTION AND CONSTRUCTION METHOD OF PROBE

The appearance of the probe is similar to that of the usual cylindrical Langmuir probe and therefore the cylindrical probe theory is applicable. In this case, however, the probe consists of a center wire insulated from an outer conductor by a glass tube (Fig. 1). Albedo electrons are collected at the center wire through a window which has been cut in the outer conductor and insulator. To insure that only albedo electrons are collected, the window faces away from the ion source and does not extend more than 180° around the probe. Factors which determine the design of the size and shape of the window are the spatial resolution desired, the sensitivity of the current measuring equipment, and the application of the particular probe. The probe constructed for the preliminary tests contained a

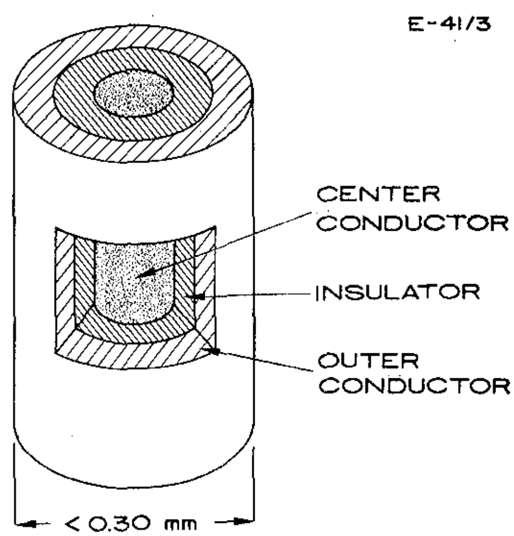

Fig. 1.
Window probe. The measured albedo electrons are collected at the center wire which is exposed by the window cut in the probe.

window of about 1/8 in. in length and 10^{-3} cm^2 in area. Leakage current between the center wire and outer conductor was eliminated by maintaining them at identical potentials.

To construct such a thin probe, a strand of tungsten wire is etched to the proper diameter and strung through a very fine length of glass tubing. This tubing is subsequently heated to cause the glass to adhere to the wire. Silver is electroplated onto the glass to make a conducting coating which may be maintained at any desired potential. To cut the window, a template is prepared which, when placed over the probe, exposes the desired area of the window. The window is then created by sandblasting away the outer conductor and the insulator to expose the center wire.

THEORY

The original Mott-Smith, Langmuir[1] probe theory is thought to be nearly valid for positive probe potentials because, for such a small probe, the sheath should be "normal" in the shadow region. The theory will not apply exactly because of the lack of cylindrical symmetry and because of the depth of the collecting surface below the outer conductor; however, very close approximation to the idealized case can be achieved by careful probe design.

Mott-Smith and Langmuir showed that the volt-ampere characteristic of such a probe is degenerate with respect to the type of electron energy distribution for positive probe potentials. In particular, for a Maxwellian distribution or for a flux of monoenergetic unidirectional electrons, the probe characteristic is

$$i = KA_w I \sqrt{1 + \frac{V}{V_o}}$$

where $K = \frac{2}{\sqrt{\pi}}$ in the former case and 1 in the latter. In both cases, i is the current collected, A_w the window area, I the current density which existed before the probe was inserted, V the potential of the probe with respect to the plasma, and V_o the characteristic energy of the electrons.

It is desired to find I and V_o, and both can be found easily if the plasma potential is known. When $i = 0$, then $-V = V_o$, and the characteristic energy is known to be equal to $-V$. When $V = 0$, then $i = KA_w I$, and the undisturbed current density can be calculated to within a factor of K, which is small in the cases considered.

Because the probe operates in a streaming plasma there will exist a shadow region behind it in which no high energy ions will be found. If this void region is kept small compared to a Debye length the electron distribution within it will not vary appreciably from that predicted by the normal theory. For this reason it has been attempted to keep the size of the probes considerably smaller than a Debye length, which in the case of most plasmas investigated is about 1 mm.

MEASUREMENT OF SLOW ION BACKGROUND WITH WINDOW PROBE

In order to observe slow ions created in the beam by charge-exchange or gas ionization, the window probe was biased negatively. While searching for slow positive ions, the window was directed away from the high energy cesium ions. Interpretation of the results is extremely difficult, however, because of the complex characteristics (even under the most ideal conditions) of Langmuir type probes and because of the decided lack of ideal conditions for these experiments. Specifically, it is assumed that the slow ions are a result of gas ionization, but the very fact that they have undergone an ionizing collision implies that their previous Maxwellian energy distribution has been seriously altered. Thus, an adequate analysis of the window probe data would have to begin with the assumption that the gas possesses a Maxwellian distribution. We must then take account of the modifications to this distribution by the ionizing collisions and finally, we must determine the response of the probe to the modified velocity spectrum.

Fortunately, this analysis need not be performed in its entirety for useful information to be gleaned from the experimental observations. For instance, it is not unreasonable to assume that the residual gas possesses a Maxwellian distribution prior to its disturbance by the ion beam, and that the net effect of the ionizing interactions is to superpose a drift velocity on the newly ionized particles in the direction of travel of the cesium beam. There will also be newly acquired transverse components but they would not enhance the window probe current. For this reason the calculations of slow ion density from window probe measuremtns based on a Maxwellian distribution of velocities will always be smaller than the true density. It may be possible to estimate the extent of the velocity changes which occur during the ionizing interactions to obtain a better estimate of the actual slow ion density but this has not as yet been attempted.

It has not been proven conclusively that the slow positive ions are created by gas ionization although it is difficult to explain their existence by any other means. To establish firmly the source of the slow ions an experiment was performed in which different gases were used in the vacuum chamberand the variation of the positive ion densities studied as a function of pressure. Because of the varying masses and ionization cross sections, the response of the probe should vary appreciably with different gases. In particular, a factor of more than 10 exists (Table I) between the expected responses of helium and xenon. Both He and Xe were introduced into the chamber and their density was varied from 8×10^{10} particles/cm^3 to about 3×10^{12} particles/cm^3 while the slow ion concentrations were being sampled. The results are not inconsistent with the ratio of 13:1 in probe current predicted by the simple theory, but they are not reliable because of a malfunction of the cesium ion gun.

One striking aspect of these data, which has also appeared previously in data taken with the larger annular ion sources, is the existence of a fairly well-defined density level above which there are only small changes in the window current (Fig. 2). This critical point appears from the preliminary experiments not to be a function of the gas present in the chamber, but to be dependent on

TABLE I

Predicted Values of Probe Current for Various Gases

ELEMENT	$M^{1/2*}$ (atomic weight)	$\sigma_I{}^*$ at 500 V (Ref. 2) (cross section)	$M^{-1/2}\ \sigma_I^{0.8}$ (Ref. 3) (probe current)
He	0.45	0.1	0.36
Ne	1.00	1.00	1.00
A	1.40	5.0	2.6
Kr	2.02	7.0	2.3
Xe	2.54	22.0	4.7

* Relative to Ne at 1.00

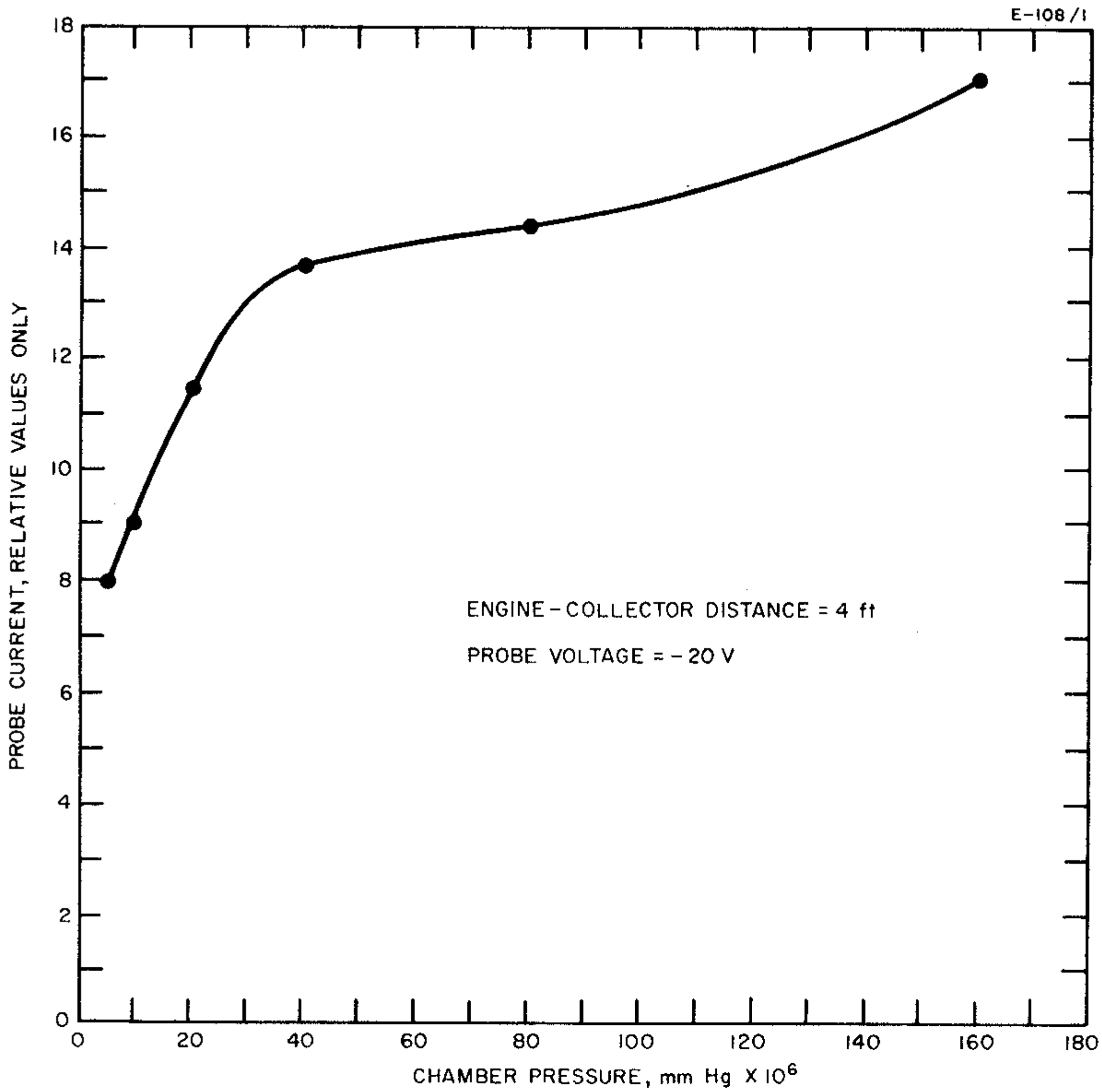

Fig. 2. Maximum window probe current versus chamber pressure.

the size of the chamber in which the experiments are being performed. Moreover, in the two sets of data which have shown this critical density, it corresponds approximately to the point at which the mean free path of the ions becomes equal to the distance between the engine and collector. The two sets of data were taken in different chambers where the engine-collector spacing, and hence the critical density, varied by about a factor of three.

While it is impossible to draw firm conclusions from such data the implication is clear that there is a significant contribution to the probe current from portions of the beam up to one mean free path from the probe, and that as the mean free path becomes less than the engine-collector distance, the attenuation of the slow ion flux by scattering roughly compensates for the increase in current caused by the increased gas density. Many more experiments will be necessary before this hypothesis will be confirmed or denied, however.

In the region surrounding an annular ion beam there appear to be two distinct regions of slow positive ions, one of which shows a definite pressure dependence. The pressure dependent portion occurs within the hollow of the annular beam where the beam does not actually strike the probe. The pressure independent portion is that which actually lies within the beam of cesium ions and may be caused by a phenomenon other than slow ions. In order to calculate the density of slow ions from the current measured by the window probe it is necessary to make several assumptions. The equation employed in these studies, (eq. (1)), is one derived by Schulz and Brown[3] in which grossly simplifying assumptions are made. It is used because the data obtained in these preliminary studies probably do not merit a more sophisticated treatment, and accuracy better than a factor of two would be fortuitous.

$$n_B = \frac{I_w}{A_w e} \left(\frac{kT_-}{\epsilon M} \right)^{-1/2} \qquad (1)$$

where

I_w = window current

A_w = area of window

e = electronic charge

ϵ = base of natural logarithms

T_- = electron temperature (taken to be 12,000°K)

k = Boltzmann constant

M = mass of positive ion .

We will first consider the pressure independent part which appears at the two positions where the high energy ions actually strike the probe as the probe is swept through the beam (Fig. 3). Since there is no pressure dependence, it is unlikely that these slow ions are created by interaction ofthe cesium ions with the residual gas. A possible explanation is that the charge-exchange process is creating slow positive ions which might be collected at the window of the probe. In this process a high energy cesium ion interacts with a neutral cesium atom which was emitted un-ionized from the hot tungsten surface, removing an electron from the atom to replace the ion's missing electron.

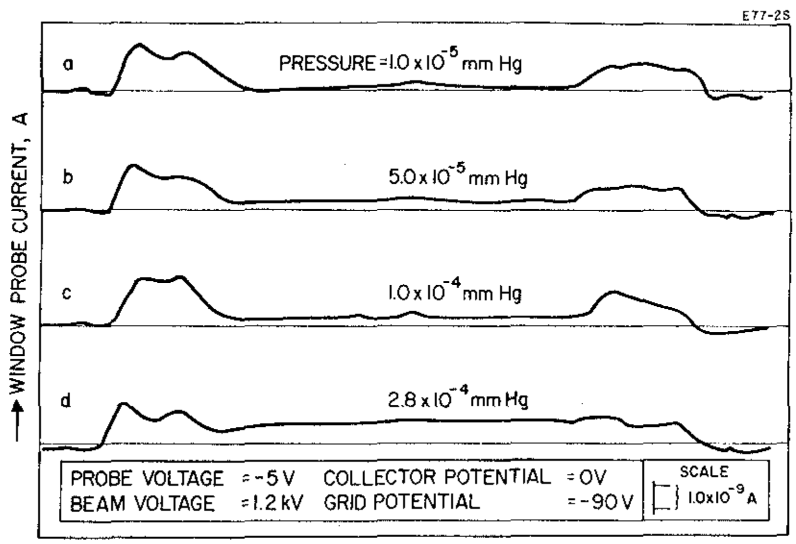

Fig. 3. Profiles of slow ion concentration in the annular ion beam with the window probe facing away from the engine.

After the interaction there remains a slow-moving cesium ion and a high energy cesium atom; these slow ions will certainly contribute to the background plasma if they are present in sufficiently abundant quantities. The cross section for this process is reasonably well known[4] and from the measured window currents it is possible to calculate the density of neutrals necessary to create the observed plasma. Such a calculation is not extremely accurate because of simplifying assumptions which must be made concerning the energy distribution of the slow ions. Values of the neutral cesium density necessary to produce the observed plasma density are calculated from (2), below, and a typical result corresponding to the data of Fig. 3 yields a neutral particle density of about $5 \times 10^{11}/cm^3$. This is much higher than the neutral density anticipated, making charge exchange an unlikely contributor to the observed currents.

$$n_o = \frac{v}{L}\left(\frac{J}{e}\,\sigma_{EX}\right)^{-1} n_B \qquad (2)$$

where

n_o = neutral cesium density

n_B = random plasma density

e = electronic charge

v = velocity of slow ions (taken to correspond to a Maxwellian temperature of 1500^oK)

L = a characteristic dimension of the ion beam (2 cm)

J = high energy cesium ion current density

σ_{EX} = cross section for charge exchange .

Some typical data, presented in Table II below, show the random plasma density (n_B) varying with beam density; this was to be expected for any reasonable process. In all cases, however, the neutral particle density would have to be extremely high to account for the presence of such a dense plasma of slow ions. It appears that, for the time being, the presence of the pressure independent portion of the plasma must remain without adequate explanation.

The portion of the plasma inside the annulus shows a distinct pressure dependence which probably results from gas ionization. To check this hypothesis it is necessary to calculate the cross section for gas ionization of air by cesium ions and to compare the value deduced with values ascertained by other methods. The cross section for gas ionization is calculated from

$$\sigma_I = \frac{e n_B}{N_o J \tau_1} \quad ;$$

where J is the current density in the ion beam, N_o the density of particles in the residual gas, and τ_1 the length of time a newly created gas ion lingers in the vicinity of the ion beam. To establish τ_1, a characteristic dimension of the ion beam (8 cm) is divided by the velocity of a 300°K air molecule. The results of such calculations based on the data of Fig. 3 are presented in Table III. Remarkable consistency of the calculated values of σ_I result when the possible large errors in nearly all the quantities used in the calculations are considered. From these data a value of σ_I equal to $4 \times 10^{-17} cm^2$ might reasonably be adopted for comparison with previously determined values of σ_I. This result is presented in Fig. 4, and is certainly not in contradiction to the anticipated result. On the basis of these data it seems safe to conclude that the pressure dependent part of the slow ion plasma is the result of ionization of the residual gas.

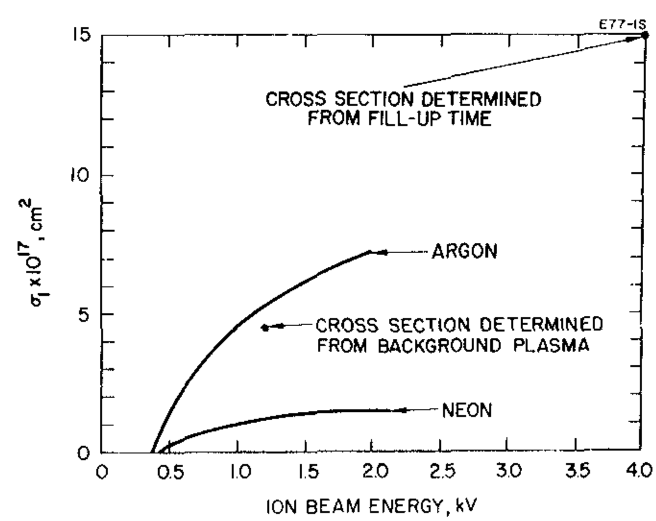

Fig. 4.
Cross section for ionization by cesium ions of argon and neon (Rf.2) and of air (these experiments.

TABLE II

Dependence of Slow Ion Density on Cesium Ion Beam Density

Density of High Energy (1.2 kV) Ion Beam ($1/cm^3$)	Density of Slow Ions n_B ($1/cm^3$)
3.3×10^8	1.4×10^8
1.3×10^8	0.6×10^8
0.7×10^8	0.2×10^8

TABLE III

Calculation of σ_I from Plasma Density Measurements

Cesium Beam Voltage = 1.2 kV

Data from Fig. 3 Curve	$N_o\left(\frac{1}{cm^3}\right)$	τ_1(sec)	J(A/cm^2)	$n_B\left(\frac{1}{cm^3}\right)$	σ_I(cm^2)
a	3.5×10^{11}	1.7×10^{-4}	1.2×10^{-4}	3.6×10^6	8.2×10^{-17}
b	1.7×10^{12}	1.7×10^{-4}	1.2×10^{-4}	7.2×10^6	3.4×10^{-17}
c	3.5×10^{12}	1.7×10^{-4}	1.1×10^{-4}	7.2×10^6	1.8×10^{-17}
d	9.8×10^{12}	1.7×10^{-4}	1.15×10^{-4}	2.6×10^7	2.2×10^{-17}

Regardless of the cause of the slow ion plasma, its presence is obviously of great importance to simulation considerations. The existence of a plasma of density comparable to that of the ion beam will drastically alter the potential distribution across the beam and will therefore affect the distribution of electrons responsible for the neutralization of the ion beam. Although the level of slow ion density which can be tolerated while still maintaining an adequate state of simulation has not been demonstrated analytically, it would seem safe to operate with the slow ion density at less than 1% of the beam density. Based on this criterion and on the data presented here, it appears that the pressure must be maintained below 5×10^{-6} mm Hg to assure a sufficiently low level of slow ion density.

It is also possible to obtain the cross section for the interaction which liberates electrons to neutralize the ion beam by measuring the fill-up time —the length of time required for a completely unneutralized beam to become neutralized by these spurious electrons. The cross section obtained in this manner will be greater than the actual gas ionization cross section for two reasons. First, it is difficult to be sure that all the electrons have been removed from the ion beam, and second, other sources such as interactions with the vacuum chamber walls and collector may contribute electrons. The cross section for gas ionization by cesium ions of argon and neon has been investigated[2,5] and the values obtained are shown in Fig. 4. While these curves are not directly applicable to the interaction being investigated because the residual gas had approximately the composition of air, it might be expected that the corresponding curve for cesium ions in air would be between those for neon and argon since the molecular weight of air lies roughly halfway between neon and argon.

If we represent the fill-up time by τ_f, the density of the residual gas by N_o, and the velocity of the cesium ions by v then the cross section for production of the neutralizing electrons is given by[6]

$$\sigma_I = \frac{1}{N_o \tau_f v} \quad .$$

In Table IV are tabulated values of σ_I calculated for N_o varying by more than an order of magnitude. The values of τ_f in Table IV were taken from the data displayed in Fig. 5. It is encouraging that the σ_I's thus tabulated show such remarkable consistency despite the possibility of appreciable errors in both N_o and τ_f. These results would lead to the adoption of a value of 1.5×10^{-16} cm^2 for σ_I at 4.0 kV, about a factor of two higher than anticipated. The consistency of the results, however, is encouraging and the high values obtained for σ_I are not inconsistent for the reasons already noted.

TABLE IV

Cross Section for Liberation of Neutralizing Electrons Calculated from Fill-up Time Measurements

$N_o\left(\frac{1}{cm^3}\right)$	τ (sec)	$v\left(\frac{cm}{sec}\right)$	σ_I (cm^2)
1.4×10^{11}	4×10^{-3}	7.6×10^6 (4kV)	2.3×10^{-16}
4.6×10^{11}	2×10^{-3}	7.6×10^6	1.5×10^{-16}
1.8×10^{12}	5×10^{-4}	7.6×10^6	1.5×10^{-16}
3.5×10^{12}	3×10^{-4}	7.6×10^6	1.3×10^{-16}

MEASUREMENT OF THE ELECTRON ALBEDO WITH THE WINDOW PROBE

In order to eliminate the chance of interactions of the beam with the collector that would affect the probe current, the beam was pulsed and the length of the ion pulse was maintained at less than 25 cm while the distance from the probe to the collector was about 2 m. Therefore, at no time was the beam in contact with the probe and the collector simultaneously. Secondary electrons emanating from the collector were suppressed by means of a grid. That they did not contribute to the probe current under any conditions, however,

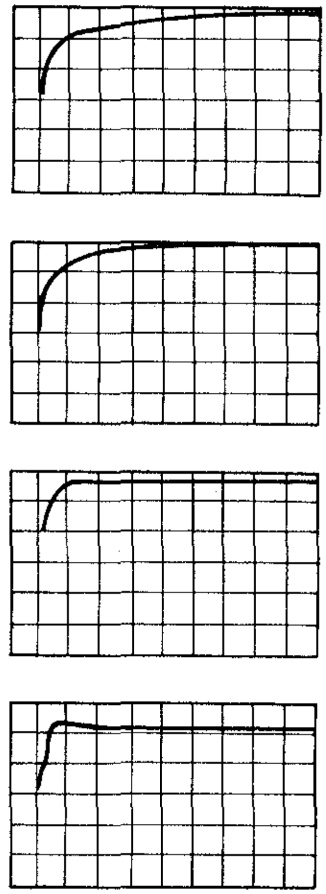

Fig. 5. Effect of pressure on fill-up time.

Collector distance = 10 ft
Collector potential = + 90 V
Pulse length = 5 μsec
Pulse amplitude = 600 V
Scope setting:

(a) collector current = 2 mA/division

(b) time scale = 0.5 msec/division.

was demonstrated by varying the grid voltage from -90 V to +270 V with respect to the collector which, in turn, was at -90 V with respect to ground. No change in probe current was noticeable throughout the range of grid voltages. It is also impossible, for purely geometrical reasons, that a significant number of electrons from the collector should reach the window of the probe unless directed by some means such as the ion beam.

Using the value of 6 V determined by independent Langmuir probe measurements to describe the electron energy in an ion beam containing 10^8 ions/cm^3, an electron density of 5×10^7/cm^3 was calculated for the albedo electron component from data obtained with the probe. Profiles of albedo electron distribution across an annular ion beam have been obtained (Fig. 6) and show many interesting qualitative aspects of ion beam behavior.

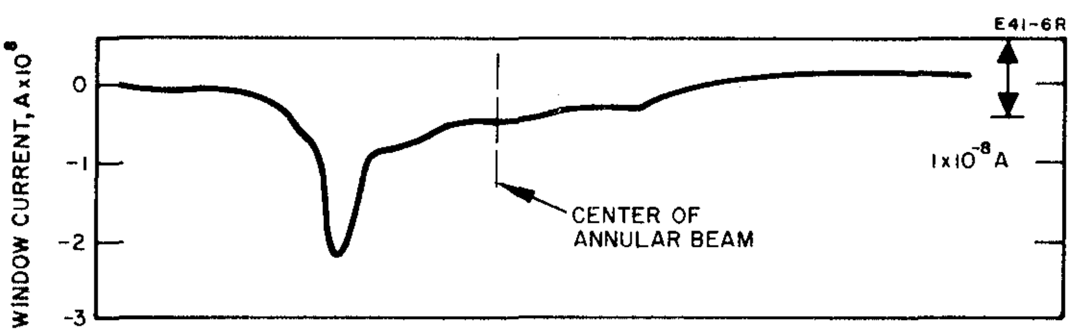

Fig. 6. Time-averaged spatial albedo electron distribution of pulsed cesium ion beam. The existence of a single peak probably indicates an asymmetrical ion source.

ACKNOWLEDGMENTS

It is a pleasure to commend H. R. Friedrich, J. A. Kelley, and F. I. Krausse for their aid in the performance of these experiments and to thank Dr. J. E. Etter for his continued support of the program.

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