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SUMMARY

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An experimental investigation of two methods for producing a hydrogen plasma was conducted. One of the two methods was a hot-cathode discharge, while the other was a modified Philips-ionization-gage (PIG) discharge. The plasma properties investigated were ion diffusion, electron density, electron temperature, mean electron energy, plasma potential, and plasma current profile.

The modified PIG discharge produced too small a plasma column to be satisfactory. It was possible with the other sources to form a 5-centimeter-diameter plasma column having a density of 8.5×10^{11} electrons per cubic centimeter at a pressure of 2 microns and a discharge supply current of 15 amperes. The electron density is shown to be a function of current density and is compared with the results of other investigators. The configuration having the filament negative with respect to the plasma chamber minimized ion diffusion. The thermal electron temperatures as measured by the Langmuir probe were 2.3 to 8.4 electron volts; the temperatures of the primary electrons as measured by the spectrometer were 23 to 55 electron volts.

Author

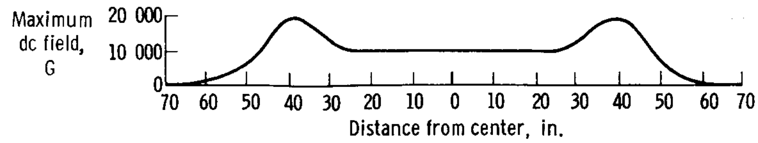
INTRODUCTION

Experiments on ion-cyclotron-wave generation require plasmas with densities of about 10^{12} ions per cubic centimeter or greater (refs. 1 to 3). In an ion-cyclotron-wave experiment conducted at the NASA Lewis Research Center, the radio frequency (RF) power was unable to form such a plasma by itself (ref. 4). It was decided, therefore, to generate a plasma that was independent of the RF source.

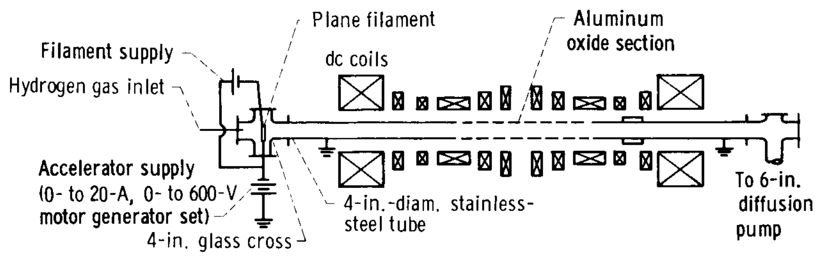
Besides producing the proper ion density, the method of generation was to meet the following objectives:

(1) The cathode should be located outside of the magnetic mirror to provide maximum length for plasma experiments.

(2) It should be simple to fabricate and install.



(a) Variation of magnetic field.



(b) Schematic of magnets and vacuum chamber.

Figure 1. - Schematic of experimental apparatus.

(3) It should have long life under intermittent operating conditions.

(4) The plasma should be at least 4 centimeters in diameter under the RF coil.

Two devices, each of which was run in different geometric configurations, were investigated with these objectives in mind. One of the devices was a heated cathode which used the vacuum chamber wall as an anode to form a hot-cathode discharge, while the other was designed to use the vacuum chamber wall as the second cathode for a modified Philips-ionization-gage discharge. This second device could also be operated as a normal hot-cathode discharge. Both types were operated with their cathodes located in the outer part of the mirror field at one end of a magnetic bottle.

During the present study, numerous diagnostic techniques were employed to determined additional characteristics of the hydrogen plasma. These studies served the twofold purpose of perfecting the techniques for later use and, at the same time, of more completely describing the plasma being used. In addition to some special probes devised for the experiments, the diagnostic techniques used were such standard devices as a microwave interferometer, a spectrometer, and Langmuir probes. The results obtained are presented as a function of magnetic field and beam characteristics and are compared, when possible, with results reported in references 5 to 7.

EXPERIMENTAL APPARATUS

Magnet and Vacuum Chamber

A schematic of the experimental apparatus (ref. 4) with one of the cathodes installed is shown in figure 1. The vacuum chamber is a 9-foot-long, 4-inch-diameter tube consisting of a 33-inch-long aluminum oxide center section with stainless-steel end sections. The axial magnetic field has a 2 to 1

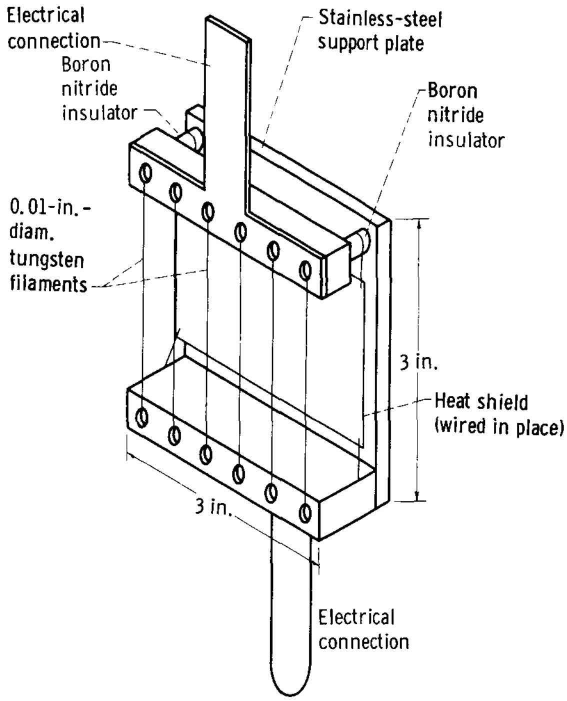


Figure 2. - Plane filament support.

mirror ratio, can operate continuously, and may be varied in strength up to 10 000 gauss between the mirrors. The magnetic field is about 15 percent of the flat field at the cathode location.

A commercial grade of hydrogen gas was fed into one end of the vacuum chamber and was pumped out the other end. The flow rate, and thus the pressure, was regulated by means of a variable leak. The pressure was measured by means of a McLeod gage mounted about 35 inches downstream of the center of the test chamber, which is about 105 inches from the hydrogen inlet. Under the preceding conditions there was a pressure drop of a factor of 2 from one end of the test section to the other end.

The direct-current power supplies used for the studies consisted of a 0- to 600-volt, 0- to 20-ampere motor generator set for the discharge supply and a 0- to 50-volt, 0- to 80-ampere filament supply. A ballast resistor was placed in series with the discharge supply during the tests to ensure stable operation of the discharge.

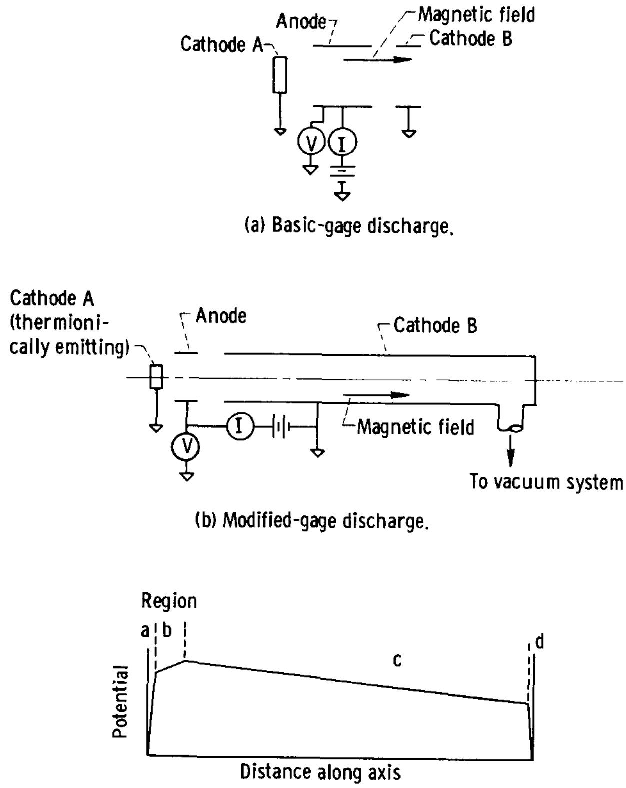
Plasma Sources

Hot-cathode discharge. - A sketch of the plane filament (PF) electron source is given in figure 2. The support structure was of stainless steel with boron nitride insulators. A tungsten heat shield was placed behind the filaments. This electron source was used with different numbers of filaments, as shown in table I. The source was operated with the filaments at a negative potential so that the grounded, stainless-steel vacuum chamber could be used as the anode. The electrons were thus accelerated by the field existing between

TABLE I. - FILAMENT CONFIGURATIONS

OF PLANE FILAMENT HOLDER

Configuration	Number of filaments	Filament diameter, in.
PF-1	1	0.02
PF-2	2	.02
PF-6	6	.01



(a) Basic-gage discharge.

(b) Modified-gage discharge.

(c) Potential distribution in modified gage.

Figure 3. - Philips-ionization-gage configurations.

the cathode and the vacuum chamber. Their motion would be primarily along the magnetic field lines. Some of the electrons undergoing deflecting collisions within the magnetic bottle would be reflected between the mirror fields until additional collisions permitted their escape. Neutral particles would be ionized along the path of the primary beam. The potential distribution for such a system is described in reference 8 (p. 250). This source was located about 62 inches upstream of the center of the system, at a point where the magnetic field was 15 percent of the central uniform field.

Modified-Philips-ionization-gage discharge. - The other device investigated was designed to operate as a Philips-ionization-gage (PIG) discharge. The basic form of a PIG discharge is schematically illustrated in figure 3(a). The cathodes are grounded, and a positive potential is applied to the anode (ref. 9, p. 152). Electrons formed at cathode A are prevented from reaching the anode by the magnetic field present and are accelerated towards cathode B. Cathode B forms a reflecting barrier for electrons and causes them to oscillate between the cathodes and experience many collisions before reaching the anode. Any ions formed between the anode and cathode B are accelerated to the right. The ions modify the potential distribution so that a sufficient number of electrons are able to penetrate beyond cathode B to maintain a neutral plasma.

The form of the PIG discharge used for this study differs from that of figure 3(a) in that the hollow cathode is replaced by a long cylinder as indicated in figure 3(b). In the present investigation this cylinder is the stainless-steel vacuum chamber of figure 1. The electrons enter cathode B and collide with one another before being reflected at the far end. In the absence of a magnetic field the axial potential distribution should resemble that shown in figure 3(c). Electrons that are emitted from cathode A are accelerated through the space-charge sheath that exists in region a. The electrons are decelerated somewhat and experience inelastic collisions in region c while region d is a space-charge sheath that reflects the electrons. This arrange-

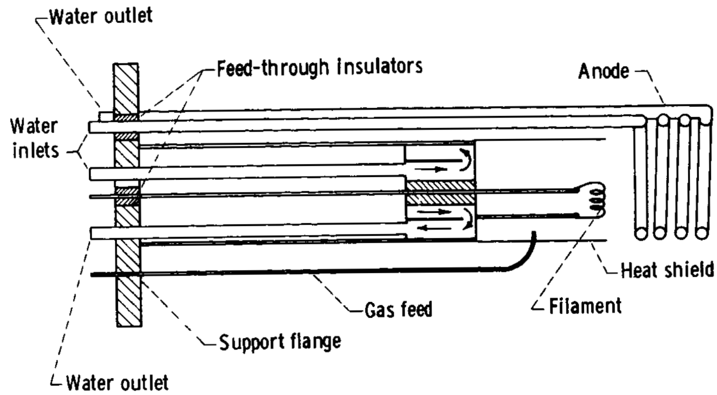


Figure 4. - Philips-ionization-gage plasma source.

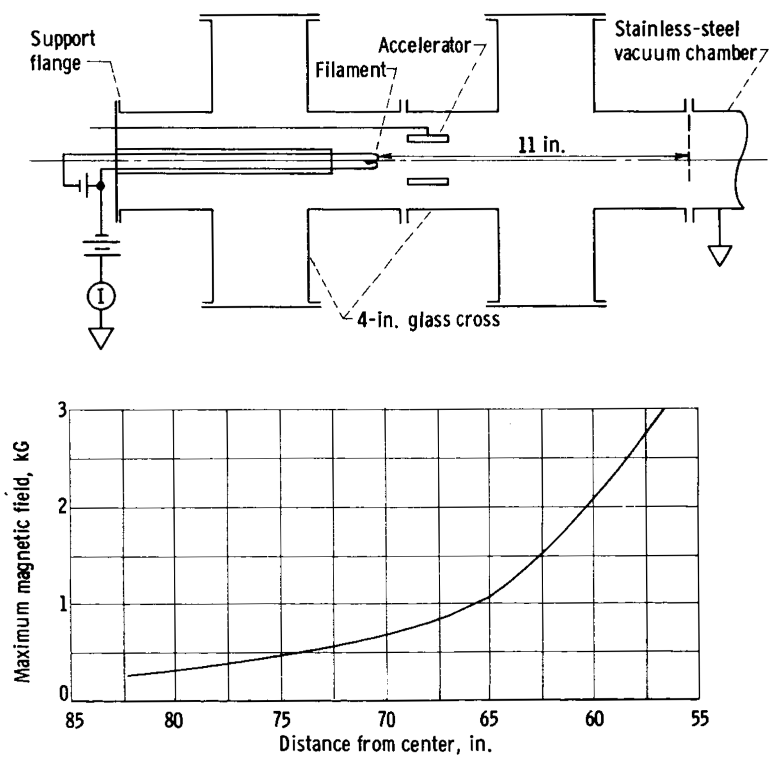


Figure 5. - Location and power supply connections of modified Phillips ionization gage and variation of magnetic field. Magnetic field rises to 20 kilogauss, reaching peak 45 inches from support flange.

ment differs from that of the simple PIG in that the plasma internal to the PIG is being studied.

A sketch of the emitting cathode and anode of the PIG is given in figure 4. The filament consisted of a 7.5-inch-long, 0.030-inch-diameter piece of tungsten wire which was wound in the form of a spiral and supported by 1/8-inch-diameter tungsten rods that were water cooled at one end. The anode consisted of four turns of 1/4-inch-diameter stainless-steel tubing wound on a $2\frac{1}{2}$-inch-diameter

TABLE II. - CONFIGURATIONS USED WITH PHILIPS-IONIZATION-GAGE SOURCE

Configuration	Filament	Anode
PIG	Ground	Positive
FN	Negative	Floating

form and spaced to be $1\frac{1}{2}$ inches long. A molybdenum heat shield was placed around the filament. Both the anode and the body of the PIG were water cooled.

In the PIG mode of operation the cathode was at ground potential, while the anode was at a positive potential of 55 to 115 volts. A second mode of operation was to bias the filament negatively with respect to ground and to use the grounded vacuum chamber walls as an anode. The electrode that normally serves as an anode was no longer needed and was left floating; thus, a second cathode was not used in this arrangement. A diagram showing the location of this device with respect to the vacuum chamber is given in figure 5, along with details of the power supply connections and the magnetic field distribution.

The main features of these two modes of operation are summarized in tables I and II. These modes will hereinafter be distinguished by the use of the abbreviations given in the tables. (FN refers to filament negative with the PIG device, while PF refers to plane filament.)

DIAGNOSTIC METHODS AND EQUIPMENT

Density and Temperature Measurements

An 8-millimeter microwave interferometer was used to measure space average values of the electron density. Complete details of the system and its operation are given in appendix A.

Langmuir probes were used to measure apparent values of the electron temperature and ion density. A detailed discussion of the Langmuir probes and the data reduction is given in appendix B.

The Langmuir probes used for radial profile measurements were inserted into the plasma by means of a hydraulically operated probe actuator that was capable of moving the probe into the plasma at a preset rate and then rapidly withdrawing it. The rapid withdrawal was needed to prevent the probe from being destroyed by plasma bombardment. The control panel of this actuator was provided with a voltage output that was proportional to the position of the probe. It was thus possible to obtain plots of probe current against position for a fixed probe voltage or plots of probe floating potential against position by means of an x,y-recorder.

Probe floating potentials were measured by connecting the probe to the y-axis of an x,y-recorder and connecting the x-axis input to the probe position voltage. The electron temperatures and plasma potentials were measured by connecting the probe as shown in figure 6. The probe power supply was set at a fixed voltage, the probe was swept into the plasma, and the current was recorded as a function of position. The power supply was then set at a different voltage, and this procedure was repeated. The family of curves obtained in

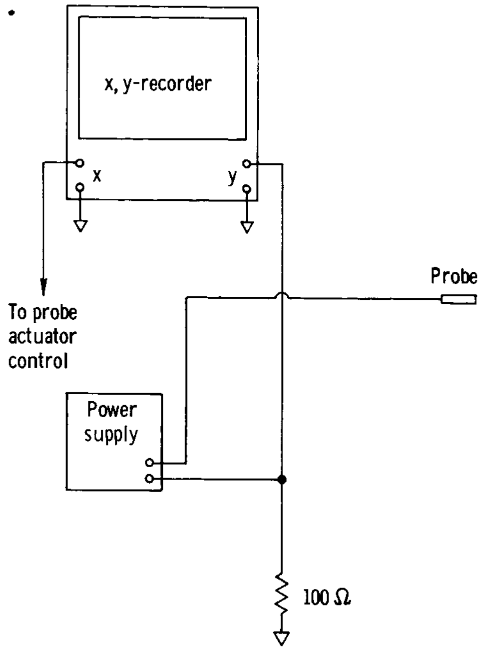


Figure 6. - Langmuir-probe measuring circuit.

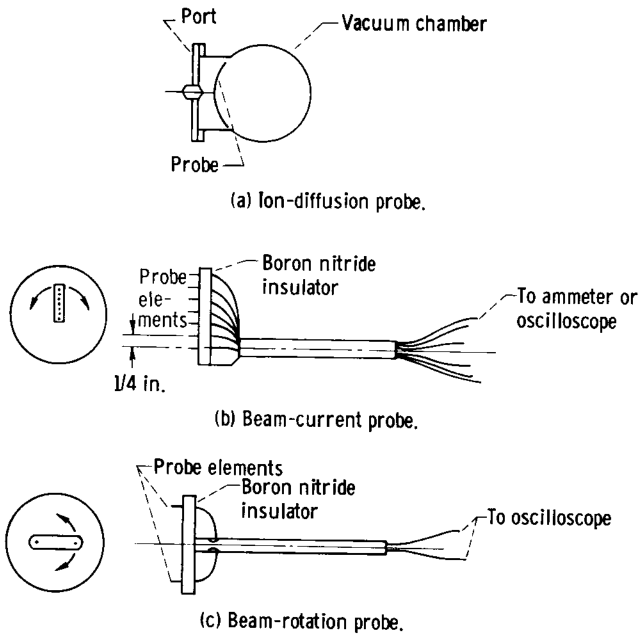


Figure 7. - Miscellaneous probes.

this manner consisted of probe current against probe position for constant probe voltage. Cross plots were then made to give standard current-voltage curves for selected probe positions. The analysis was then performed in the manner described in appendix B.

Miscellaneous Probes

Three other probes designed to answer specific questions about the plasma were also used in this series of experiments.

Ion-diffusion probe. - The ion-diffusion probe consisted of a wall segment placed at one of the 3-inch ports and having the same curvature as the vacuum chamber wall. This wall segment was made part of the chamber wall but was insulated from it. The floating potential of the segment was measured in order to gain information about ion or electron diffusion to the walls. A diagram of this probe is shown in figure 7(a).

Beam-current probe. - The beam-current probe consisted of seven parallel elements mounted 1/4 inch apart on a common support. This support was placed along a diameter of the vacuum chamber with one of the endmost elements positioned at the axis of the vacuum chamber. The probe was located at the vacuum pump end of the apparatus and was placed 47 inches from the center of the system. The support could be rotated to sweep the area of a 3-inch-diameter circle. A diagram of this probe is given in figure 7(b). A rotary switch was provided so that any six of these elements could be grounded, while the seventh would be connected to ground through a milliammeter. Measurements made with elements at various locations gave information about the current distribu-

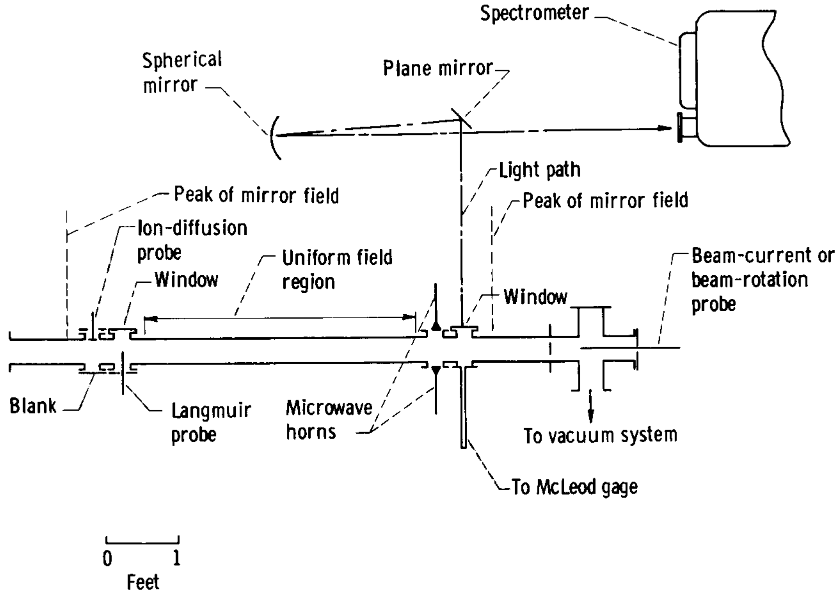


Figure 8. - Top view of experimental apparatus showing positions of diagnostic equipment.

tion in the plasma column.

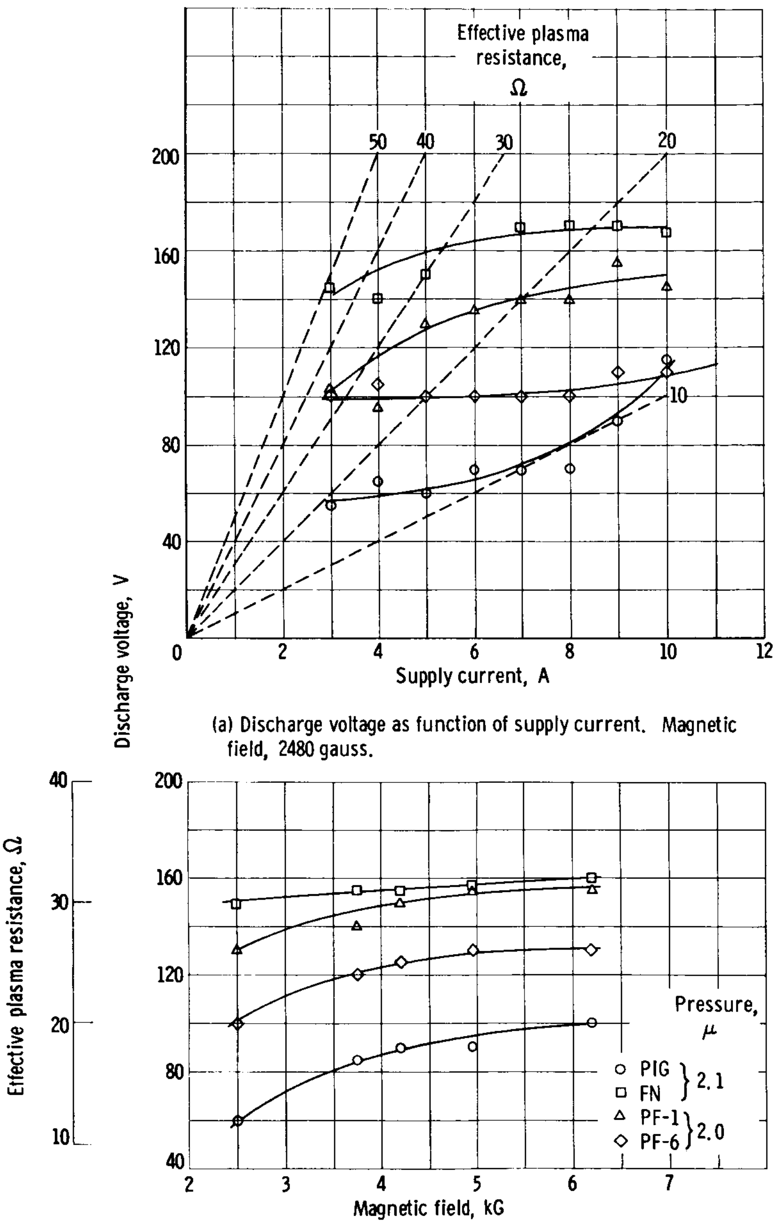
In a later test, the milliammeter was removed and replaced by a coaxial cable that was connected to an oscilloscope and terminated. When connected in this manner, the probes were used to investigate periodic plasma motions.

Beam-rotation probe. - This probe consisted of two parallel elements placed 1 inch from either side of the vacuum chamber axis about 47 inches from the center of the system. A diagram of this probe is given in figure 7(c). Voltage signals from these elements were placed on the inputs of a dual-beam oscilloscope by means of properly terminated coaxial cables. The probe was designed to determine whether periodic motions of the plasma were due to plasma rotation.

Spectrometer

A 1.5-meter Bausch and Lomb (model 33-83-05-11) spectrometer was placed in a position where it could view the plasma column. It was used to determine the average electron energy from the ratio of the measured intensities of selected pairs of molecular lines and was also used to look at the intensity ratio of atomic to molecular hydrogen lines to determine the effect of discharge supply current and magnetic field on the atom-molecule ratio. The computation was made by using the values of the relative cross sections for exciting some singlet and triplet lines (ref. 10).

Figure 8 is a diagram of the vacuum chamber showing the locations of the various pieces of diagnostic equipment.



(a) Discharge voltage as function of supply current. Magnetic field, 2480 gauss.

(b) Discharge voltage as function of magnetic field strength. Supply current, 5 amperes.

Figure 9. - Operating characteristics of discharge.

RESULTS AND DISCUSSION

General Properties of Emitter and Discharges

The filament temperature was very important for proper operation of the sources. If the filament temperature was too low, the discharge current was temperature limited, and any attempt to raise the current by increasing the anode voltage caused local heating of the filament by ion bombardment. This gave rise to a very narrow plasma column and shortened filament life considerably. Increasing the filament temperature too much produced an unstable plasma.

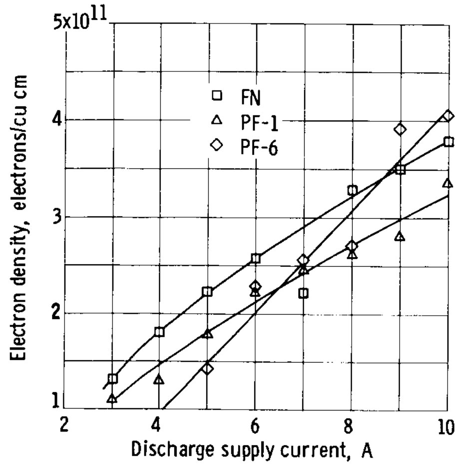


Figure 10. - Effect of discharge supply current on electron density. Magnetic field, 2480 gauss; pressure, approximately 2 microns.

Operating the filaments at or near the beginning of the temperature-limited region gave the most stable results. Visual observations of the plasma made at the spectrometer port showed that most of the electron-emitter configurations could give a plasma about 4 to 5 centimeters in diameter at a magnetic field of 2480 gauss in the region between the mirrors. The plasma produced by the modified PIG discharge radically decreased in size as the field was increased, while the plasma produced by the plane filament was relatively insensitive to the magnetic field. The operating characteristics of the different source configurations are shown in figure 9. The current-voltage relation at a single value of the magnetic field (fig. 9(a)) shows a considerable amount of data scatter. This may be attributed to the fact that no means were available for setting the filament temperatures accurately from run to run. An attempt was made to control filament temperature by keeping the filament current constant, but the voltage control on the filament power supply was not precise enough to ensure good repeatability. The PIG configuration was observed to give rise to the largest amount of sputtering during these tests, as evidenced by the deposition of a thin metallic-appearing film on the viewing ports.

The effective resistance of the discharge is also presented in figure 9. The decrease in resistance with increasing current is a well known effect caused by the increase in electron density with discharge current. The effective resistance generally also increases with increasing magnetic field (fig. 9(b)) even for those configurations wherein the electrons need not cross the field lines. A similarly strong influence of magnetic field on discharge properties has been observed by others (refs. 5 and 6).

Figure 10 shows the variation of electron density obtained with the microwave interferometer as a function of discharge supply current for three of the configurations. The modified PIG data are not presented because the plasma was not sufficiently reproducible and the electron density was about one order of magnitude lower. Also, the modified PIG gave only a 1-centimeter-diameter beam. Figure 10 indicates that the electron density is primarily a function of discharge supply current for the hot-cathode-discharge configuration and that the electron emitter design is of secondary importance. Since the PF-6 filament configuration best met the requirements set forth in the INTRODUCTION, it was decided to concentrate the remainder of the investigation on this type of electron source.

Plasma Characteristics

Plasma current profile and plasma rotation. - The current profile of the plasma was measured by using the seven-element probe of figure 7(b). The probe was placed outside of the magnetic mirror but at a point where the value of the

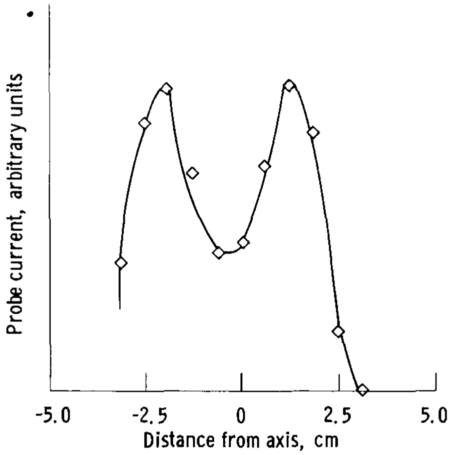


Figure 11. - Vertical beam profile for PF-6 cathode. Beam current, 1 ampere; pressure, 2 microns; magnetic field, 2480 gauss.

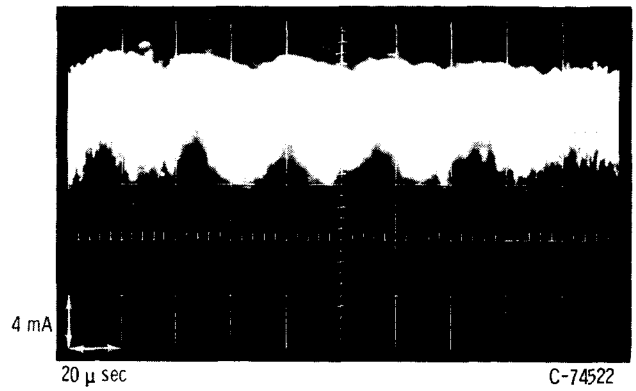


Figure 12. - Typical plasma oscillation results. PF-6 cathode; supply current, 1 ampere; pressure, 2 microns; magnetic field, 2480 gauss.

magnetic field was the same as that in the central region. Since the magnetic field had the same value at the probe position as it did in the uniform field region, the plasma column should have approximately the same size in both places. The probe was placed so that it could be rotated about the axis and was used to determine whether the plasma was axially symmetric.

The PF-6 cathode was operated at a discharge supply current of 1 ampere, and the current drawn by each element of the probe was measured. The probe was placed in a vertical position, the currents were measured, the equipment was shut down, and the probe was rotated 90°. Both vertical and horizontal plasma profiles were obtained in this manner. The various sets of data were normalized to agree along the axis.

The profiles along the horizontal and vertical diameters were found to have similar shapes. The vertical current profile is shown in figure 11. This type of current distribution can be explained in either of two ways: (1) the plasma was cylindrically symmetrical and hollow, or (2) the plasma was solid but was off axis and was rotating as a whole about the axis. If the second hypothesis were true, an oscilloscope connected in place of the current meter could observe a periodic current change. A properly terminated coaxial cable was connected from the probe to an oscilloscope. The results are shown in figure 12, which is a display of the current at a point 1/2 inch away from the axis at an oscillation of 31 kilocycles per second. This measurement by itself does not prove plasma rotation because this signal could just as easily represent a longitudinal plasma oscillation.

A rotation of the plasma about the axis should not be too surprising. Since the plasma is not at ground potential, a radial electric field exists between the plasma core and the vacuum chamber wall. This electric field, in combination with the magnetic field, should set up an $\vec{E} \times \vec{B}$ drift velocity given by $v = E/B$. For rotation, $v = \omega R$ so that

$$\omega \sim \frac{E}{RB} \qquad (1)$$

where

ω frequency of rotation

E electric field strength

R plasma radius

B magnetic field strength

Hoh (ref. 11) has discussed this type of rotation for a Penning-type discharge in some detail. Although the discharge investigated herein is not of the Penning type, the same considerations should be valid because similar conditions exist in the plasma.

To determine whether the measured frequency agreed with this rotation mechanism, the magnetic field was raised to twice its previous value (to 4960 G), and the frequency of oscillation was measured. This frequency was found to be 45.3 kilocycles. According to equation (1), the frequency ratio for the two fields should be

$$\frac{\omega_1}{\omega_2} = \frac{E_1 R_2 B_2}{E_2 R_1 B_1}$$

Although the electric field was unknown, it was assumed that it would be directly proportional to the plasma potential along the axis of the vacuum chamber. From Langmuir-probe measurements this potential increased by a factor of 3; thus it was assumed that $E_2 = 3E_1$. The plasma radius seemed from visual observations to be independent of the magnetic field. Thus, the expected fre-

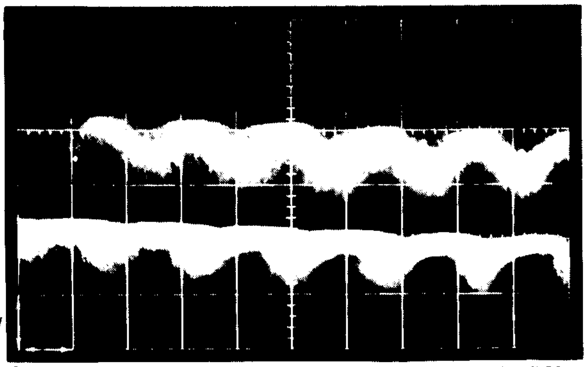


Figure 13. - Results of measurements with the beam rotation probe. PF-6 cathode; supply current, 1 ampere; pressure, 2 microns; magnetic field, 3720 gauss.

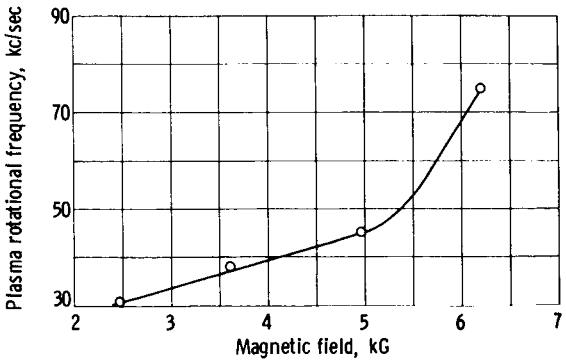


Figure 14. - Effect of magnetic field on plasma-rotation-frequency with PF-6 cathode. Pressure, 2 microns; discharge supply current, 1 ampere.

quency ratio is

$$\frac{\omega_1}{\omega_2} = \frac{E_1 R_1 2B_1}{3E_1 R_1 B_1} = \frac{2}{3}$$

which agrees quite well with the measured ratio 31/45.3.

A more direct means of demonstrating that the plasma rotates was by means of the probe of figure 7(c). Simultaneous measurements of the plasma oscillation on both sides of the axis should give signals that are 180° out of phase if the plasma is rotating as a whole. The results of this measurement (fig. 13) tend to confirm that the plasma rotates.

Further measurements were taken with the beam-current-profile probe to determine the variation of the frequency as a function of the magnetic field, and they are presented in figure 14.

Ion diffusion. - The floating potential of the ion-diffusion probe was measured in order to compare ion diffusion in the various configurations. Figures 15 and 16 show the results of the probe measurements as a function of supply current and magnetic field. It can be seen that the floating potential of the probe is positive, which indicates that the diffusion to the walls is predominately due to ions. The PIG configuration gave the most ion diffusion. At higher magnetic fields figure 16 indicates that the ion diffusion was reduced for all configurations. The relatively large amount of ion diffusion for the PIG source was expected because previous measurements of axial plasma potentials in an oscillating electron plasma source (ref. 12) showed that the plasma potential drops to about one-third of the accelerating potential while the plasma is under the reflecting cathode. Since the arrangement investigated in

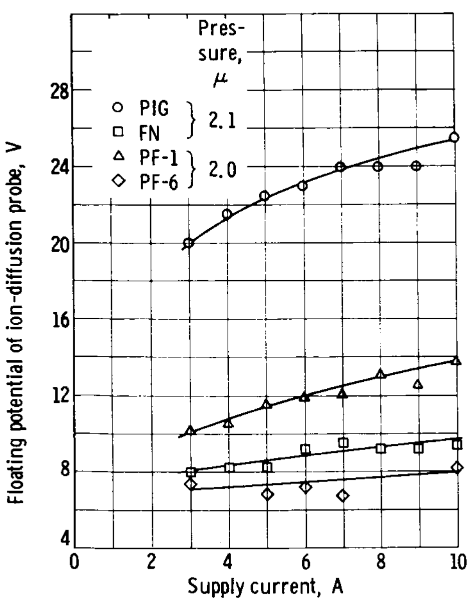


Figure 15. - Effect of supply current on ion diffusion for different sources. Magnetic field, 2480 gauss.

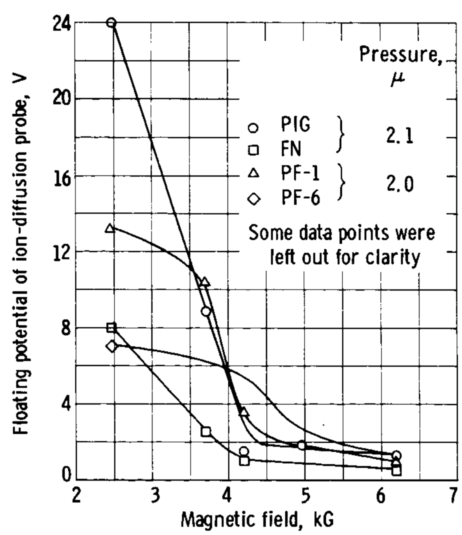


Figure 16. - Effect of magnetic field on ion diffusion for different sources. Supply current, 5 amperes.

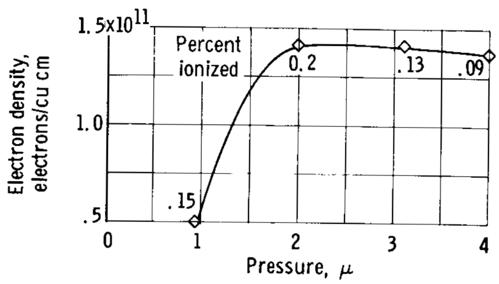


Figure 17. - Effect of pressure on electron density with PF-6 filament. Magnetic field, 2480 gauss; discharge supply current, 5 amperes.

reference 12 was quite similar to the modified PIG configuration investigated herein, it was expected that the plasma would take on a slight positive potential with respect to the vacuum chamber. The other configurations that are similar to those described in reference 8 were expected to take on an axial potential near that of the anode. Since these configurations have the anode grounded and the cathode biased negatively, the plasma would tend to take on a slight negative potential. The electric field set up between the plasma and the wall would thus tend to enhance ion diffusion to the walls for the PIG case but would hinder it for all the other cases.

One should keep in mind the fact that the potential at which the wall probe floats will be a function of both the plasma diameter and the potential difference existing between the plasma and the wall. Thus, the preceding measurements are to be interpreted as indicating trends only.

Microwave-density measurements. - The optimum operating pressure was determined by measuring the electron density as a function of pressure for one particular configuration. The optimum pressure was defined as that pressure which gave the highest percent ionization consistent with the requirement that the plasma density be above 10^{11} ions per cubic centimeter. As can be seen from figure 17, at reasonable operating conditions, a pressure of about 2 microns is optimum. All further tests were therefore performed at this pressure.

The variation in electron density with discharge supply current and magnetic field for a PF-6 filament is presented in figures 18 and 19, respectively. The increase in electron density with discharge supply current is expected from a consideration of the ionization cross sections of atomic and molecular hydrogen. The increase in electron density with magnetic field is probably due to the better containment provided. The maximum electron density of about 8.5×10^{11} electrons per cubic centimeter is in reasonable agreement with the work of other authors (refs. 5 and 7).

The results of four experimental investigations of plasma production are summarized and compared in table III. The normalized electron density is obtained by dividing the values of electron density by 8.5×10^{11} electrons per cubic centimeter. Similarly, the tenth column gives the normalized discharge current densities obtained by dividing each entry in the fourth column by 0.765 ampere per square centimeter. The last column presents figures of merit, which compare the discharge supply currents required to form a plasma of a given diameter and electron density. Supply current was chosen as a basis of comparison (instead of supply power) because the required voltage, and thus the power, is a strong function of the geometry of the system. The last column indicates that the four devices listed (which vary widely in their degree of complexity) do not differ greatly in this figure of merit. It thus appears that the simplest possible apparatus may be as good as more

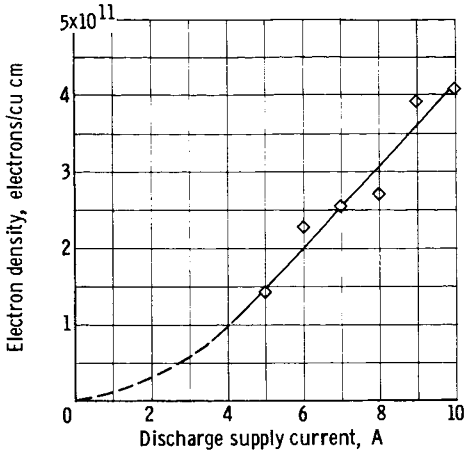


Figure 18. - Effect of discharge supply current on electron density for FN configuration. Magnetic field, 2480 gauss; pressure, approximately 2 microns.

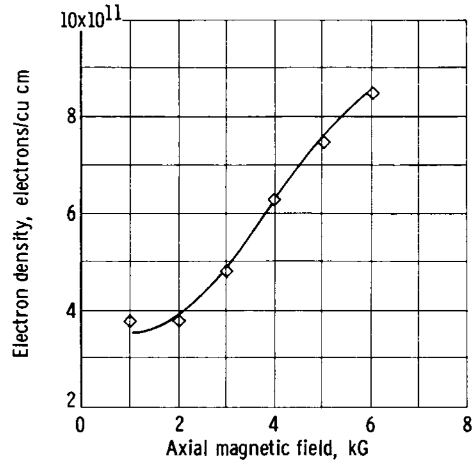


Figure 19. - Electron density as function of magnetic field with PF-6 source. Discharge supply current, 15 amperes; pressure, 2.2 microns.

TABLE III. - RESULTS OF EXPERIMENTAL INVESTIGATIONS OF PLASMA PRODUCTION

Reference	Beam diameter, cm	Discharge supply current, I, A	Current density, J, A/sq cm	Gas	Pressure, μ	Electron density, N_e, electrons/cu cm	Method	Normalized electron density, $\mathcal{N}$	Normalized current density, $\mathcal{J}$	Figure of merit, $\mathcal{N}/\mathcal{J}$
This report	5	15	0.765	Hydrogen	2	8.5×10^{11}	Microwave	1	1	1
7	1	1.4	1.115	Hydrogen	5	4	Langmuir probe	0.47	1.46	0.32
7	1	1.4	1.115	Hydrogen	5	10	Estimate	1.18	1.46	.81
6	2.5	80	16.3	Helium	---	200	Microwave	23.5	21.3	1.1
5	5	15	.765	Helium	3	10-20	Microwave	1.18-2.35	1	1.18-2.35

elaborate apparatus if electron density is the primary consideration. The devices described in references 5 and 6 have somewhat higher figures of merit than the device described herein, but this may be due to their use of helium, which is considerably easier to ionize.

Comparison of the current density with the electron density implies that the attainment of higher electron densities is primarily a matter of increasing the discharge supply current in this range of gas pressures.

Langmuir-probe-density and floating-potential measurements. - Ion-density measurements were made with a 0.01-inch-diameter Langmuir probe. The apparent radial variation in ion density is presented in figure 20. The fact that this is an apparent density is stressed because the plasma column rotates in an asymmetric manner about the axis of the vacuum chamber; hence it does not have its maximum density along the axis as indicated in figure 20. The density pro-

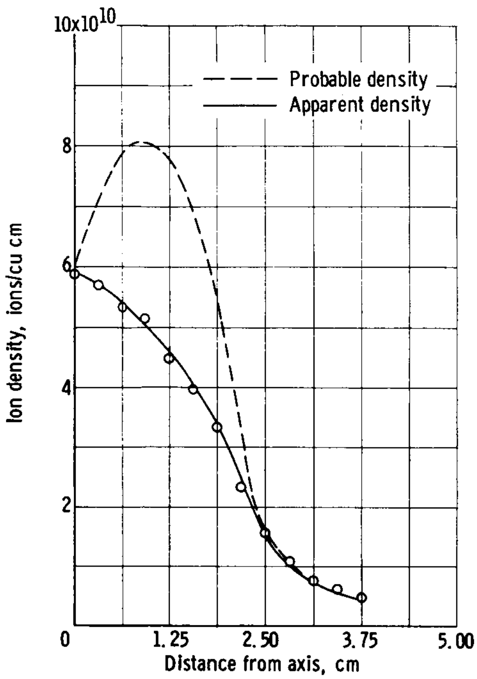
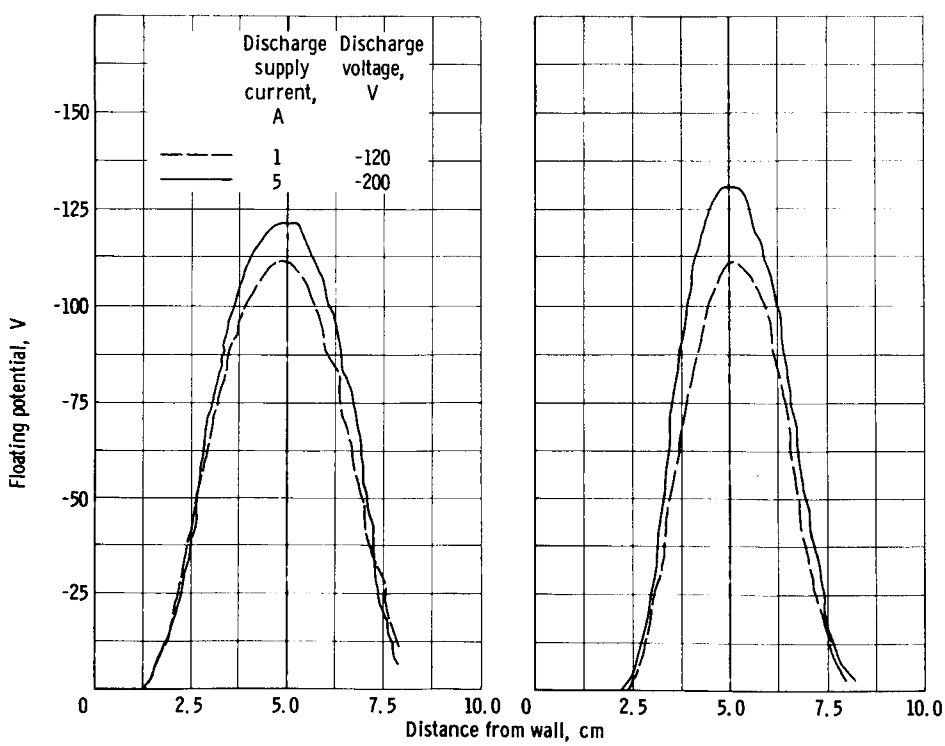


Figure 20. - Apparent ion density profile of 3-ampere discharge. Measurements made with Langmuir probe; axial magnetic field, 2480 gauss; pressure, 2 microns.

file is probably similar to that shown by the dotted line in figure 20. This ion density determination is in reasonable agreement with the microwave results in figure 18.

The floating potentials of a Langmuir probe as a function of plasma radius were measured for the PF-2 and PF-6 filaments by using a probe 1 millimeter in diameter and 2 millimeters long. The purpose of these measurements was to determine the symmetry of the plasma column. The results of the runs for the PF-6 filament are shown in figures 21(a) and (b) for magnetic fields of 2480 and 4960 gauss, respectively. These floating-potential measurements were made at low supply currents, where the energy of the primary electrons was low. For these conditions, it appears from figure 21 that the maximum potential of the plasma is near cathode potential, that it is not strongly affected by an increase in discharge supply current (which increases electron density), and that the size of the plasma column is not strongly affected by a change in magnetic field.



(a) Magnetic field, 2480 gauss.

(b) Magnetic field, 4960 gauss.

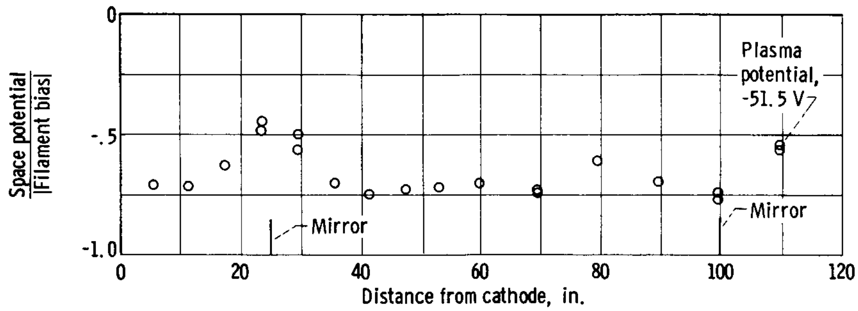
Figure 21. - Probe floating potential as function of distance into vacuum chamber with PF-6 filament. Pressure, 2.05 microns.

A 0.005-inch-diameter probe was installed and was used to probe along the axis of the vacuum chamber. The probe was designed to sample the beam at a point 1/2 inch below the axis of the vacuum chamber, but it was found impossible to maintain this position accurately as the chamber was traversed axially. This inability to position the probe properly gave rise to the data scatter of figure 22.

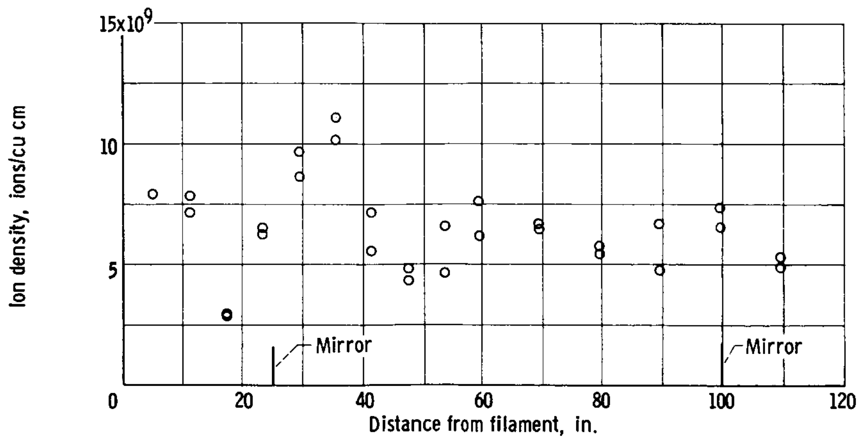
Figure 22(a) shows that the plasma is closer to the cathode potential than to the anode (grounded). This is rather unexpected because most of the potential drop should have been across a thin cathode sheath, at least for zero magnetic field (ref. 8, p. 250). It appears instead that most of the drop occurs at the anode; the reason for this cannot be explained at the present time. The rise in plasma potential near the first mirror may be due to the beam narrowing so that, in effect, the plasma moved away from the probe.

The ion densities (fig. 22(b)) show considerable scatter but are otherwise quite uniform along the length of the plasma column. The rise in density at the mirrors is probably again due to the pinching down of the plasma in this region.

Electron energies. - The electron temperatures for the PF-2 and PF-6 filaments were determined with a Langmuir probe having a diameter of 1 millimeter



(a) Axial variation of space potential field.



(b) Axial variation of ion density.

Figure 22. - Axial variation of space potential and ion density. Magnetic field, 2480 gauss; pressure, 2 microns; beam current, 1 ampere.

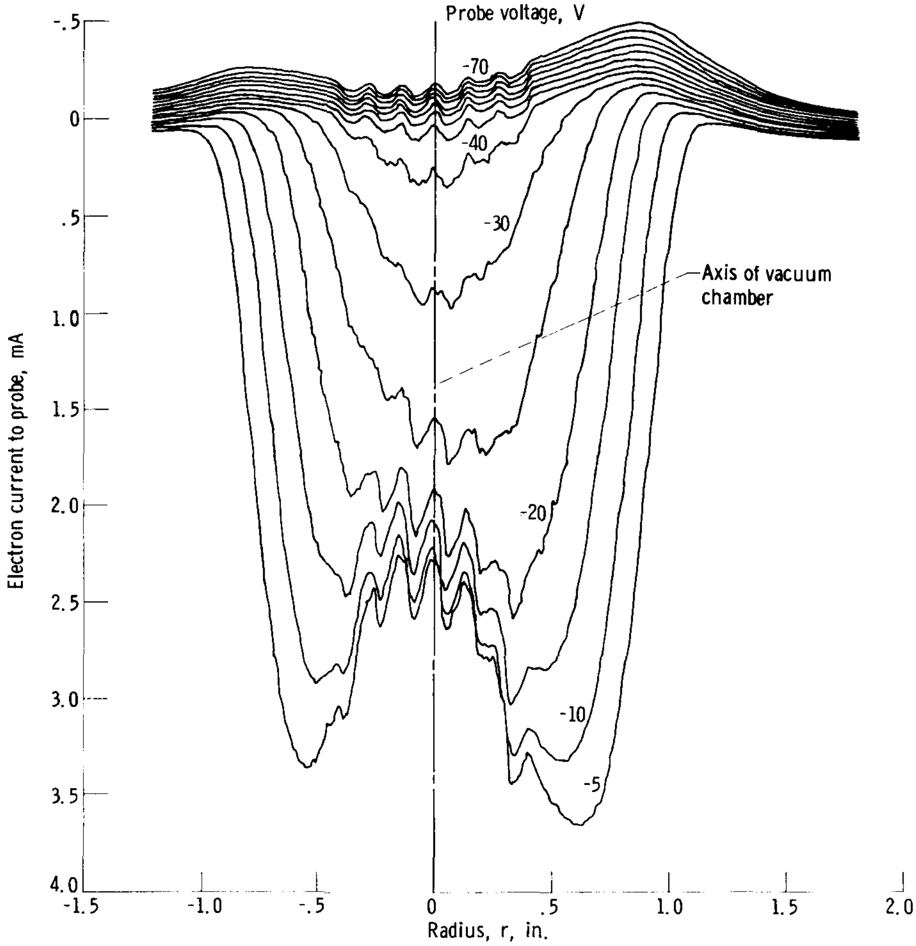


Figure 23. - Typical Langmuir-probe data.

and a length of 2 millimeters. A typical set of curves that were obtained is shown in figure 23. This set of curves cannot be interpreted directly in terms of electron density because the probe saturation current is a strong function of electron temperature. The probe voltage was varied from 5 to 70 volts to obtain this set of curves. The influence of the six filaments can clearly be seen as well as the relative decline of electron currents along the axis. Electron temperature and plasma potentials were found from these data by means of a semilog plot of probe current against probe voltage. Representative values are given in table IV. The electron temperature across the beam of the PF-6 filament varied from 2.3 to 5.0 electron volts at a field of 2480 gauss and from 5.9 to 8.4 electron volts at a field of 5960 gauss, the higher temperatures being away from the axis of the column. The electron temperatures determined in this manner with the Langmuir probe are thermalized electrons and have energies different from those of the electrons in the primary beam of the plasma.

The energy of the electrons in the primary beam was measured at a point 97 inches downstream of the filament by means of the optical spectrometer. The energy was determined by observing the intensity ratio of the 4628-angstrom molecular singlet line to the 4554-angstrom molecular triplet line. The known ratio of the relative intensities as a function of energy (refs. 10 and 13) was then used to compute the energies. The intensity ratio of the 4580-angstrom line to the 4554-angstrom line was also measured and gave results in agreement with the preceding measurements.

There was no correlation between the various configurations when electron energy was plotted against accelerating voltage. A plot of electron energy against discharge supply current gave a straight line of a different slope for each configuration tested; however, there was a strong correlation between the electron energy and the discharge supply power for the various plasma

TABLE IV. - LANGMUIR-PROBE DATA AT CENTER OF BEAM

Pressure, μ	Magnetic field, G	Electron temperature, V	Plasma potential, V	Filament type
2.05	2480	3.4	-32.5	PF-6
2.05	4960	8.0	-97.5	PF-6
1.91	2480	5.7	-37.5	PF-2
1.85	4960	6.6	-75.0	PF-2

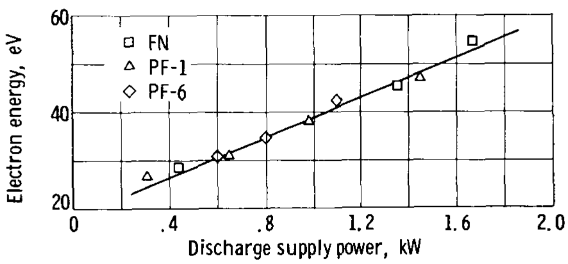


Figure 24. - Primary electron energy as function of supply power. Magnetic field, 2480 gauss; pressure, 2 microns.

sources (fig. 24).

<u>Ratio of atoms to molecules</u>. - The spectrometer was used in an attempt to measure the ratio of atoms to molecules as a function of beam power. The atomic lines looked at were the Balmer γ, δ, and ϵ, while the molecular lines were the 4628-angstrom singlet and the 4554-angstrom triplet. Slight changes in the intensity ratio of an atomic line to a molecular line were observed with changes in discharge supply power, but these changes could have easily been caused by changes in electron energies. That is, the intensity of the Balmer lines increases with increasing electron energies, while the intensity of the molecular lines decreases (ref. 10). Since it was observed that the average electron energies increased with discharge supply power, the observed changes in the intensity ratio of atomic to molecular lines were probably caused by the change in intensity with electron energy and would have been greater if the atom-molecule ratio had changed. It was thus concluded that the ratio of atoms to molecules was quite insensitive to beam power and probably changed but little, if at all. Quantitative results for these ratios could not be obtained because of the lack of absolute cross-sectional data.

SUMMARY OF RESULTS

An experimental investigation of two devices for the generation of a plasma was conducted to determine their suitability for use in an ion-cyclotron heating experiment. One of the sources was a modified Philips-ionization-gage (PIG) discharge. The other source consisted of a cathode with different numbers of filaments, with the vacuum chamber walls serving as the anode. The modified PIG was also used as a hot-cathode discharge by biasing the filament negative with respect to ground, floating the accelerator, and using the vacuum chamber walls as an anode. All the tests of the separate cathode were performed with the cathode at a negative potential. Hydrogen gas was used for all the tests.

Visual observations of the plasma showed that the modified PIG discharge gave a very narrow plasma that was quite sensitive to magnetic field, whereas the other sources gave plasma of about 4 to 5 centimeters in diameter when the central portion of the magnetic field was in the range 2480 to 6200 gauss. The plasma produced by the modified PIG discharge was considered too small for use in the ion-cyclotron heating experiment.

The particle loss to the walls was due predominately to ions, and this ion diffusion could be reduced by having the filament at a negative potential and by increasing the magnetic field. A method of plasma formation which puts the electron source at a potential that is negative with respect to the vacuum chamber is thus the better of the two methods investigated for obtaining a plasma of maximum ion density.

Energies of the primary electrons were found to be a function of discharge supply power and were independent of the configuration tested. These electron energies ranged from 23 to 55 electron volts.

The ratio of atoms to molecules was found to be insensitive to discharge supply power.

The optimum operating pressure in the range of field strength used was found to be about 2 microns. The electron density at this pressure varied from 1×10^{11} to 4×10^{11} electrons per cubic centimeter (for a magnetic field of 2480 G) as the discharge supply current was varied from 3 to 10 amperes. The electron density was also found to be a function of the magnetic field, reaching a maximum of 8.5×10^{11} electrons per cubic centimeter at a field of 6000 gauss with a discharge supply current of 15 amperes. Comparison of the results with those of other ion sources indicated that the electron density, as a function of discharge current density, was relatively independent of the type of source. The only requirement on the number and size of the filaments is that they be capable of carrying the supply current.

The temperature of the thermal electrons in the plasma, as measured with a Langmuir probe, varied from 2.3 to 8.4 electron volts.

The plasma column rotated about the axis of the vacuum chamber. The frequency of rotation was related to the plasma floating potential and to the value of the magnetic field.

It was concluded from these studies that a simple hot-cathode discharge is capable of producing the necessary ion densities for ion-cyclotron wave experiments.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 2, 1965.

APPENDIX A

MICROWAVE INTERFEROMETER

A schematic of the microwave interferometer is given in figure 25. The microwave signal was electronically interrupted at a rate of 1000 cycles per second to permit the use of alternating-current amplification. The detected signal, consisting of a 1000-cycle-per-second square wave, was amplified and displayed on an oscilloscope. The output of the oscilloscope vertical amplifier was converted to a direct-current signal, and its amplitude was read out on a digital voltmeter. The reading of the digital voltmeter was directly proportional to the power level of the microwave signal detected because the detector was operated in the region where voltage is directly proportional to power.

In order to compute the electron density, the amplitudes of the signals in the reference arm and the plasma arm and the sum of the signals in both arms were measured both with and without a plasma. The amplitude of the signal in the reference arm was measured by closing the flap attenuator in the plasma arm and thus preventing any signal from following that path. The amplitude of the signal in the plasma arm was measured by having both flap attenuators in the open position. The phase difference between the signal in the reference arm and the one in the plasma arm for each case (plasma and no plasma) was then computed from the following relation:

$$\cos \theta = \frac{\frac{P}{P_1} - \left(1 + \frac{P_2}{P_1}\right)}{2\sqrt{\frac{P_2}{P_1}}}$$

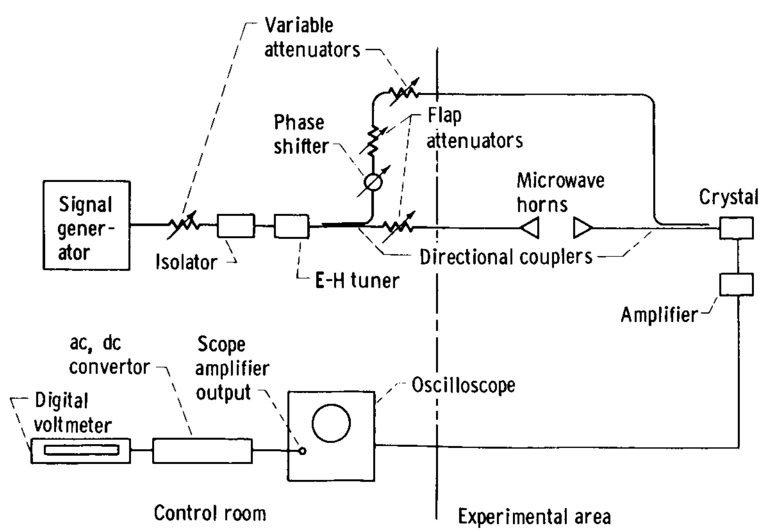


Figure 25. - Schematic of microwave interferometer.

where

θ phase angle

P total power in two arms

P_1 power in reference arm

P_2 power in plasma arm

The electron density was then found by using the difference in phase angles along with the following relation:

$$N_e \simeq 2.07\times10^9 \, f(\Delta\theta/L)$$

where

N_e electron density, electrons/cu cm

f generator frequency, kMc/sec

$\Delta\theta$ phase-angle change, deg

L path length through plasma, cm

Further details about this type of system are given in reference 14.

APPENDIX B

LANGMUIR PROBE

A Langmuir probe consists of a small rod, plate, or sphere immersed in the plasma and connected to an external source of variable direct-current voltage. This source of voltage is adjusted to different values, and the probe current is measured.

When the probe is sufficiently negative with respect to the plasma potential, only positive ions will be accepted, and the probe will collect the saturation ion current. As the voltage is made less negative with respect to the plasma, electrons are able to reach the probe, and the ion current is decreased until a certain voltage is reached where the ion and electron currents are equal. The potential at this point is called the floating potential of the probe. As the voltage is made positive with respect to this floating potential, the electron current increases rapidly until a point is reached where all of the random electron current is collected by the probe. Further increase in the voltage should not increase the probe current, although some increase is noted in practice. A typical Langmuir-probe curve is shown in figure 26.

If the electron energy distribution is Maxwellian, the rise in current will be an exponential function of voltage over some region, and it has been shown (ref. 9, p. 196) that a plot of the log of the current, measured from the ion saturation current, against the voltage will give a straight line whose slope is a measure of the electron temperature. This procedure seems to work even in the presence of a magnetic field, although no theoretical justification can be given.

In the absence of a magnetic field, the Langmuir probe can also be used to measure the electron density at the point where it is placed. An approximate measurement of ion density can be made even in a magnetic field, if the probe size is made small compared with the ion gyromagnetic radius (ref. 9, pp. 197-198). For these measurements, probes of 0.01 inch diameter were constructed. Low discharge currents were used because of the danger of destroying the probes. Even if the probes are not damaged, the density measured can be an order of magnitude in error because of a temperature effect (ref. 15).

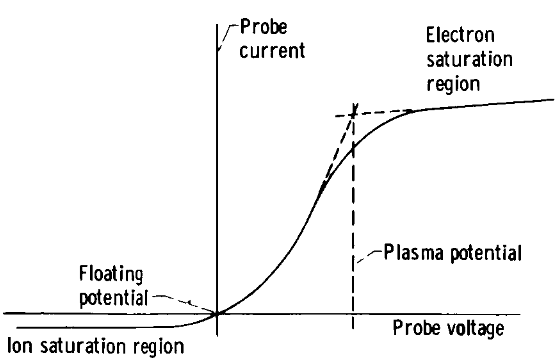


Figure 26. - Typical Langmuir-probe curve.

To analyze the data, the square of the ion current was plotted against probe voltage at a given radial location in the plasma, and the slope of the straight line formed was determined. The local ion density, in particles per cubic meter, was then calculated from the following relation (ref. 6):

$$N_i^2 = \frac{2.01 \times 10^{30}}{A_p^2} \frac{d(I_i^2)}{dV} M$$

where

A_p probe area, sq m

I_i ion current, A

V probe voltage

M mass number of ion

The ion density must, in any plasma, be very closely equal to the electron density.

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