PLASMA OSCILLATIONS IN A LOW PRESSURE ARGON DISCHARGE

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ABSTRACT

This work is a continuation of the investigations started by Howard T. Webb and Alan S. Garner, and as extended by Eugene E. Shoults and John A. Flynn in the field of plasma oscillations in low pressure argon discharges at the United States Naval Postgraduate School.

The basic tube was modified to incorporate a Philips Impregnated (L-dispenser type) cathode. Emphasis was given to analysis of the plasma oscillations and the tube characteristics by the Langmuir probe method.

The writers wish to express their appreciation to Professor Normal L. Oleson for his continued encouragement, suggestions and support, and to Professor A. W. M. Cooper for his advice and cooperation. Thanks are also due to Mr. Milton K. Andrews of the Physics Department for his technical support.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction.

The mounting problems in the control of fusion reactions; the quest for explanation of solar and radio astronomical noise phenomena; and allied investigations indicate the need for further basic research in the field of electric discharges - especially discharges at low pressures and in inert gases. This report covers plasma oscillations in low pressure argon discharges.

The term "plasma" embraces the portion of the discharge in which the ion and electron densities are high and substantially equal (1). The positive columns of glow and arc discharges are notable examples of plasmas. Ionization of the plasma is maintained primarily by electron collisions and by some photoionization. The regions are highly conducting and the negative carriers are electrons in rare gas plasmas. Thermal equilibrium among the positive ions, electrons, and neutral atoms of the gas may or may not exist. Since the positive ions are accelerated by the action of the applied electric field, the positive ion temperature may be higher than the gas temperature. Because of the greater mobility of the electrons and their small mass their temperatures will be much higher than those of the positive ions.

In general, the positive ions and electrons may be assumed to have a maxwellian distribution, but departures from this distribution have been observed (1, 2). The applied field does not necessarily produce

a departure from the maxwellian distribution in the plasma because the drift current density is generally much smaller than the random current densities of the ions and the electrons. The field does however increase the temperatures of both ions and electrons.

A large volume of plasma with the electrons and ions moving at their characteristic temperatures in random directions is necessarily neutral. However at points within the plasma there are high fields existing depending on the arrangement of the charged particles around each point. The fields change with time and electrons may gain considerable energy in passing through a series of accelerating fields with a fortuitous instantaneous configuration.

Two types of oscillations seem to be possible from the theoretical point of view; plasma electron oscillations and plasma ion oscillations. When the electrons oscillate, the positive ions in a comparative analogy have been likened to a rigid jelly of uniform density of positive charge, ne. The electrons are initially distributed uniformly with a charge density, -ne, but are free to move. The resulting restoring force brings about plasma oscillations. The positive ions also may oscillate but because of their large mass the frequency of oscillations will be much lower than the frequency of electron oscillations.

Plasma electron oscillations may transmit energy by a growing wave mechanism. A growing wave results from the excitation of plasma electron oscillations and the interaction of these oscillations with the beam. As the wave moves longitudinally through the plasma,

it tends to "bunch" the slowly drifting groups of oscillating electrons in advance of the wave and spread the groups after wave passage. As the redistribution takes place the exchange of energy between electrons and wave in a particular phase relationship increases the net energy in the wave. The wave amplitude grows exponentially reaching the maximum rate of growth when plasma frequency approaches the excitation frequency.

Another mechanism in which energy of the plasma electron oscillations may be transmitted is by modulating the velocity of the primary electrons as the latter traverse the oscillating region.

Experiments in plasma oscillations are usually carried out in gas-filled diodes or triodes employing discharges through mercury, argon, and similar gases. A diode filled with argon was used in this investigation.

Typically, the voltage profile across the tube consists of a steep rise in potential near the cathode, then a slow rise across the positive column of discharge to the anode with a sharp, small rise at the anode (9). The electrons traversing the interelectrode distance experience their major potential rise in the region near the cathode called the cathode "fall." Because the electron mobilities are greater than those of the positive ions, the cathode is surrounded by a sheath of positive ions. As electrons move away from the cathode sheath they are accelerated toward the anode producing more ionizations and attaining a maxwellian distribution of velocities as they move

through the gas and experience collisions with gas atoms and each other. At the negative glow boundary the entering electrons consist of at least two groups - fast electrons which have been produced at or near the cathode and have suffered few collisions in the dark space, and slow electrons which have made many inelastic collisions in the dark space. Since the slow electrons have energies below the ionization potential but above or at the excitation potential, they experience exciting collisions and produce emission of light from the negative glow, then recombine with positive ions. The group of fast electrons are the negative charge carriers which traverse the interelectrode space.

2. Previous Work.

In 1924 while making studies of electric discharges at low pressure using a hot filament as an electron source, Langmuir and Mott-Smith found that a large number of the primary electrons acquire velocities whose voltage equivalent was greater than the potential drop across the tube (3).

Primary electrons beyond the cathode sheath would be expected to have energies corresponding approximately to the anode potential. There was also a large number of electrons which had less energy than expected so that the average energy of the primary electrons as a group had not changed. This unequal distribution of the energy among the primary electrons is called "scattering."

Dittmer found that the region of scattering approaches the cathode as the tube current is increased and predicted that high scattering of electrons might be due to oscillations in the plasma. However he was unable to detect such oscillations (4).

In 1926 Penning observed plasma oscillations with frequencies ranging from 300 to 600 megacycles in the regions of electron scattering (5).

Langmuir and Tonks detected oscillations in the one to 1000 megacycle range and developed a theory of electronic and ionic oscillations in an ionized gas (2). They postulated that the frequency of plasma electron oscillations depended on electron concentration. Oscillations of the large positive ions were relatively slow and compared to a jelly-like region of uniformly distributed positive charge. The displacement of a group of plasma electrons in a small region of the plasma would cause a restoring force proportional to the displacement and the charge. This force would cause displaced electrons to oscillate about an equilibrium point at a frequency of

$$f_e = \left(\frac{n e^2}{\pi m_e}\right)^{1/2} \simeq 8980 \; n^{1/2} \quad c/s$$

where the average concentrations of electrons and positive ions are assumed to be equal and n is the number of particles per cubic centimeter, e is the electronic charge, and m_e is the electronic mass.

Assuming the same type of displacement for the positive ions as for electrons before, the frequency of plasma ion oscillations becomes

$$f_i = \left(\frac{n e^2}{\pi m_p + \frac{n e^2 m_p \lambda}{k T_e}} \right)^{1/2} \quad c/s$$

where m_p is the ionic mass, λ is the wave length of the plane wave or approximately equal to the displacement of the ions from an equilibrium position, and T_e is the absolute temperature of the electrons. If the displacement is small or if T_e is large, the plasma ion frequency reduces to the same form as the electron frequency, i.e.,

$$f_i = \left(\frac{n e^2}{\pi m_i} \right)^{1/2} = f_e \left(\frac{m_e}{m_i} \right)^{1/2} c/s \text{ (for singly charged ions)}$$

Langmuir and Tonks verified the above predictions with experiments. The absence of space coordinates indicates that, except for secondary factors, the electronic oscillations do not transmit energy.

Druyvesteyn and Warmoltz during their work with hot cathode discharges in 1937 observed that anomalous changes in electron velocities and concentrations occurred in very narrow regions in the plasma and advanced a hypothesis of the existence of micro-fields to explain the effects (6).

Merrill and Webb investigated the dependence of electron scattering upon plasma oscillations in a mercury arc discharge. They used a movable probe of tungsten wire to measure the intensity and position of plasma oscillations. Probe data was analyzed by the Langmuir and Mott-Smith method to determine electron and ion concentrations and

electron temperatures - a method generally used in the present investigations. Merrill and Webb confirmed the observations of Druyvesteyn and Warmoltz and detected stable periodic oscillations of considerable magnitude in narrow regions. Because the oscillations were found only in regions traversed by the primary electrons they concluded that the scattering was due to plasma oscillations. The observed frequencies agreed well with the formula derived by Tonks and Langmuir (3).

Continuing the pioneering investigations of Merrill and Webb with studies extending from 1947 to 1954, Armstrong, Emeleus, and Neill established that (a) oscillations are stable and reproducible, (b) oscillations varied in frequency and magnitude over the tube characteristics (8) and (c) the frequency of oscillation, which agreed with Tonks and Langmuir's formula, was independent of probe bias over an extended range and varied directly with gas pressure (10, 11).

In 1949 Wehner's experiments with a stablized low pressure arc discharge resulted in the discovery of an RF oscillator with tunable frequencies between 800 and 4,000 megacycles and again the observed frequencies compared with Tonks and Langmuir theory (12).

Utilizing a new technique in 1954 Looney and Brown injected a beam of high energy electrons from an auxiliary electron gun into the plasma of a D.C. discharge and excited oscillations in the plasma at the Tonks-Langmuir electron frequency (13). A movable probe showed the existence of standing wave patterns at the oscillatory energy in and around the electron beam. By detailed behavior of the frequency of oscillation and

the transitions in the standing wave patterns, the mechanism of energy transfer from the electron beam to the oscillation of the plasma electrons was established as a velocity-modulation process. However, Looney and Brown could not produce the plasma oscillation predicted by Bohm and Gross and others (14, 15).

Later in 1957, Boyd, Field, and Gould used a technique similar to that of Looney and Brown but modulated the probing electron beam with a slow electromagnetic wave. They obtained experimental verification that the maximum rate of growth of plasma oscillations occurs when the plasma frequency is linearly related to the modulation frequency (16). By producing a direct correlation between modulation and plasma frequency and demonstrating the laboratory existence of growing plasma waves, Boyd et al substantiated the previous theoretical efforts of Bohm and Gross, Haeff, and others.

The reliability of probe analysis in the investigations of electron scattering in discharges was shown by T. K. Allen (17). Allen confirmed that the oscillation intensity peaks occurred at an integral number of "beam wavelengths" between anode and cathode. He concluded that oscillation intensity fluctuations as the probe is moved away from the cathode are caused by feedback from the probe used for detection of the oscillations. The peaks correspond to the feedback being in phase with the disturbance at the cathode. Spectroscopic analysis of an argon discharge showed the abrupt appearance of scattering at a particular distance in the absence of the probe. He also described the appearance

in argon and mercury of a meniscus - a thin region of brighter plasma extending across the beam and convex toward the cathode with a dark region of similar shape on the anode side. Emanating from a region just beyond the meniscus, visible effects of primary electron scattering were observed as converging and diverging beams in the glow region.

In 1957 Allis suggested that the concentration gradient of plasma electrons is a controlling factor for the growth of plasma oscillations, theory indicating that oscillations are most likely to grow in amplitude when propagated down a concentration gradient (18). Mahaffey et al in 1958 and 1959 investigated Allis's suggestion and found at least an eighty-five percent correlation between occurrence of maxima and minima of the electron concentration, and the growth and decay respectively of oscillation intensity (19).

3. Equipment.

The equipment used can be divided into four main components as follows:

(1) Gaseous discharge tube in which a glow discharge could be continuously maintained.

(2) D. C. electrical circuit for supplying power and for controlling and measuring discharge conditions.

(3) Frequency detection and measuring equipment.

(4) Vacuum system for the evacuation and filling of the tube.

Fig. 1 is a photograph of the general experimental arrangement.

a. Discharge tube. Fig. 2 is a photograph and Fig. 3 is a detailed drawing of the tube (diode). The electrodes and probes were attached to soft iron cylindrical cores sealed in glass. This made possible the variation of interelectrode distances and probe positions by moving the iron cores with externally applied magnetic fields.

The principal probe used in this work was a cylindrical probe composed of .008 inch tungsten wire which was enclosed in a glass sheath up to 3.8 millimeters of the tip.

Some preliminary measurements were made using an insulated coiled wire probe. This probe was constructed of 112 turns of No. 36 Cerametemp * wire coiled on a ceramic core of five millimeters diameter and four millimeters long. The coil could be rotated from a position parallel to the discharge beam axis to one that was perpendicular. During remodeling of the discharge tube the coil wire was damaged and this probe was removed. It was replaced by a ring probe as shown in Fig. 3. The latter probe was not used in the experiment.

All leads to the probes and to the electrodes were made as short as possible in order to minimize inductance effects which tend to attenuate signals.

The cathode was a Philips impregnated "L" cathode ** with a two centimeter diameter face indirectly heated by a tungsten element drawing

* Manufactured by Hitemp Wires, Inc., 26 Windsor Ave., Mineola, L.I., New York

** Manufactured by Semicon of California, Inc.

seven amperes D. C. Considerable time and effort were spent in making a suitable heater element for the cathode. The design decided upon was a coiled .014 inch tungsten wire, the coil being approximately 1.5 centimeters in diameter and one centimeter in length. The element was formed by winding the tungsten wire on a brass mandrel and then heating the mandrel with a torch until the wire was sufficiently annealed to hold the desired shape.

An insulating coating was necessary for the heater so that it would not short out with itself or with the body of the cathode into which it fitted. For this purpose a thin uniform coating of Al_2O_3 was applied by the following procedure. The coil was thoroughly cleaned electrolytically in a strong NaOH solution using the coil as anode and a carbon rod as cathode. A potential of approximately five volts was applied for less than one minute which was sufficient time to remove the oxide film from the tungsten. The cleaned wire was then coated with alumina by dipping it into a thick slurry of Al_2O_3 suspended in amyl acetate. Some experimenting was required before this seemingly simple process resulted in an acceptable alumina coating on the tungsten. Another method tried was the cataphoresis process [20]. The amyl acetate slurry was diluted with an equal volume of ethyl alcohol and used as an electrolytic solution with a stainless steel anode and the tungsten coil as cathode. Various voltages were tried, but the coatings achieved were not as uniform as those resulting from the simpler dipping method.

The alumina was dried in air by passing 3.5 amperes of current through the wire for about five minutes. This resulted in an adherent coating which would stand reasonably careful handling. A harder coating could be obtained by baking in a vacuum at 1700 degrees centigrade for 15 - 20 minutes.

b. D. C. circuits. Fig. 4 diagrams the D. C. circuitry used with the discharge tube. D. C. power source for the tube was a voltage regulated power supply manufactured by Kepco Laboratories, Model 1250B. Power available was 1-1000 volts, 1-500 milliamperes. A D. C. generator supplied power for filament heating, and probe biasing was by "B" batteries. Vacuum tube volt meters were used to measure plate and probe voltages.

c. Vacuum system. Although no special attempts were made to obtain the ultra-vacuums achieved by Flynn and Shoults (21), pressures in the order of 10^{-7} mm of mercury were readily attained. All valves in the system were glass stop-cocks lubricated with Type N Apiezon grease. The diffusion pump was a three-stage air-cooled pump using Octoil-S. The major part of the system could be baked out by means of a portable oven (see Fig. 5). An induction heater was used to outgas the anode. Outgassing of the Langmuir probe was accomplished while the tube was operating by applying positive potential to the probe sufficient to cause ohmic heating of the probe.

Low pressures were measured by an ion gauge. Pressures in the operating range (one to ten microns) were measured by a Langmuir

viscosity gauge (21). Tube voltage readings also were used as an indication of tube pressures after voltage-pressure relation had been determined. Since plate voltage is a function of tube pressure (other parameters such as current and anode-cathode spacing remaining constant), a given pressure could be readily duplicated by evacuating or filling the tube until the correct voltage was obtained. Thus, if fresh argon was desired in the tube, the procedure of flushing and refilling could be quickly and accurately accomplished without relying solely on the relatively slower pressure measurement process using the viscosity gauge.

d. Detection equipment. A Tektronix Type 543 oscilloscope was used to detect oscillations of frequencies up to 20 megacycles. Higher frequencies were detected by a radio test set, AN/URM-17 which has a frequency range of 370-1000 megacycles with a threshold voltage of ten microvolts.

4. Procedure.

After assembly, the system was evacuated to the 10^{-4} mm of mercury range. The anode was outgassed with the induction heater and then the system was baked out with the oven at 460 degrees centigrade for five hours. During this time the tubing and liquid air trap of the filling system were heated to 350 degrees centigrade by means of heating tapes. Following bake out, the cathode was heated to operating temperature and the anode again outgassed with the induction heater. After the pressure was reduced to 5×10^{-7} millimeters of mercury,

the system was filled to two millimeters of mercury with spectroscopically pure argon. This evacuation and filling was repeated twice with the final pressure left at the desired operating pressure.

The first efforts were to obtain the tube current-voltage characteristics and to determine if detectable plasma oscillations were present. The results of these experiments are shown in Figs. 6 through 9. Tube pressures shown were measured by the viscosity gauge with the tube in operation. Low frequencies were detected by the oscilloscope (the oscilloscope probe was attached to the wire probe and grounded to the cathode). Measured signal voltages are shown in parenthesis on the graphs of Figs. 6 through 9. The high frequencies were detected by using the URM-17 as a sensitive radio frequency electronic micro-voltmeter with the lead-in cable terminal next to, but not touching, the wire probe lead. Voltage readings for these oscillations must be considered relative since the URM-17 was not calibrated for a matched impedance input.

By use of the cylindrical wire probe, data were obtained for Langmuir probe analysis, i.e., determination of electron temperatures, ion and electron densities, space potentials, and predicted electron and ion oscillation frequencies. Plots of the characteristics are shown in Figs. 10 through 18. Due to limited time, probe analysis was restricted to one tube pressure (2.2 microns) and one plate current (50 milliamperes). Data were taken with anode-cathode distance fixed at 1.5 centimeters and with six different probe to cathode distances. The probe was approxi-

mately five millimeters above the discharge beam axis and parallel to the cathode face.

Preliminary measurements were made with the coil probe in an attempt to detect the presence and orientation of changing magnetic fields in the discharge. Signals were observed on the oscilloscope and signal strength varied as the coil probe was rotated in the beam. With the coil axis tilted about ten degrees toward the cathode from the vertical plane, the maximum signal was detected. The signal diminished as the coil was rotated clockwise, i.e., the upper part of the coil was turned toward the anode. A minimum in the signal strength was detected when the coil had been rotated approximately 90 degrees from the position of maximum signal. With further rotation of the coil, the strength of the signals increased to another maximum at the position of 180 degrees of rotation. These results indicated a changing magnetic field in the beam with a maximum component in a plane tilted about ten degrees toward the cathode from a plane which is normal to the beam axis. Further use of this coil was curtailed when the coil was damaged and removed from the tube.

5. Results.

Low frequencies which were attributed to positive ion oscillations were detected by the oscilloscope in the range of 40-550 kilocycles. Lower frequencies were present but were found to be relaxation oscillations (23). Higher frequencies were detected from 362 to 960 megacycles and were believed to be electron oscillations. Equipment capabilities

prevented adequate coverage of the ranges 2-370 megacycles and above 1000 megacycles. The measured relative intensities of oscillations and the calculated electron densities for tube pressure of 2.2 microns are shown graphically in Fig. 19 and tabulated in Table 2. It can be seen that these properties increased to maximum values in the 10-12 millimeter range of probe to cathode distance. Also, Figs. 6 through 9 show maximum oscillation intensity at a probe-cathode distance of ten millimeters for the measurements made with tube pressure at five microns.

It was found that the wire probe characteristics changed rapidly during tube operation. It was assumed that this was primarily due to material sputtered or evaporated from the Philips cathode. To minimize this effect, it was necessary to clean the probe repeatedly. This was accomplished by applying a positive potential to the probe, causing it to draw sufficient current to heat it to cherry red.

For a cylindrical probe with an orbital-motion-limited current, the theory developed by Langmuir and Mott-Smith indicates that the square of the ion current density increases linearly with probe voltage (3), the relationship for singly charged ions being:

$$J_i^2 = \frac{I_i^2}{A^2} = \frac{2 e^2 k T_i}{\pi^2 m_i} \left[\frac{Ve}{k T_i} + 1 \right] n_i^2$$

where: J_i = ion current density to probe

I_i = ion current to probe

A = probe area

V = probe potential with respect to plasma

T_i = ion temperature

m_i = ion mass

n_i = ion density in plasma

e = electronic charge

k = Boltzmann's constant

Thus, a plot of I_i^2 versus V should result in a straight line. Further, the slope of the line can be used to determine n_i:

$$\frac{dJ_i^2}{dV} = -\frac{2e^3}{\pi^2 m_i} n_i$$

and $$n_i = \sqrt{\frac{-S\pi^2 m_i}{2e^3}}, \text{ where } S = \text{slope}$$

Under the assumptions made, n_i is also n_e (electron density) in the plasma.

Curves for square of total probe current (I_s^2) versus probe voltage with respect to anode (V_s) are shown as Figs. 10 through 12. I_i is equal to I_s in the region where the probe retarding field is large enough to repel all the electrons. As probe potential is decreased from that point all probe current should be positive ion current, and a straight line relation is predicted. However, it was found that current increased rather rapidly as the probe was made more and more negative, and the I_s^2 versus V_s plot departed from the straight line relation. This was assumed to be the result of electron emission by the probe, and the effect was increased as the probe to cathode distance was decreased. The correct I_s^2-V_s relation in each plot was taken as a line drawn through the points in the region where probe emission was not evident.

To obtain the values of I_e, the I_i^2 plot was extrapolated toward higher potentials. Using the I_i so obtained:

$$I_e = I_s - I_i$$

As long as the probe voltage retards the electrons and if the electrons have a maxwellian velocity distribution, the following relations are valid (22):

$$I_e = I_e^o \exp(-eV)/kT_e$$

$$\text{and} \quad \frac{d(\ln I_e)}{dV} = -e/kT_e$$

In order to obtain electron temperature and space potential the logarithm of I_e was plotted against probe potential with respect to anode (V_s). The plot obtained was not linear but it could be resolved more or less into two energy groups, each with a maxwellian distribution, i.e., linear relation of log I_e and V_s. Figs. 13 through 18 are plots of log I_e versus V_s and show the resolution of I_e into the two groups. The temperature of each group was determined from the slope (S_e) of its log I_e versus V_s by:

$$T_e = \frac{e}{kS_e}$$

In all plots except the one for probe to cathode distance of ten millimeters the plot of the fast group terminated at a "kink" which appeared at a point where the potential in relation to space approximated the tube drop. The reason for this "kink" is not known, but it probably can be attributed to a small group of electrons with a narrow band of energy, one which had been accelerated to tube potential and had not been scattered.

Space potential listed in Table 2 was obtained from the intersection of the two asymptotes of the log I_e versus V_s plot. Space potential can also be located on the log I_e versus V_s graph by using the predicted electron current when the probe is at space potential. This current (I_{sp}) can be calculated from the electron concentration (n_e) and the temperature of the slow group of electrons by using the relation:

$$I_{sp} = \frac{1}{4} n_e \left(\frac{8 K T_e}{\pi m_e} \right)^{1/2} e A$$

As a third method, the space potential can be fixed--theoretically--as the potential where the graph of log I_e versus V_s departs from linearity. Experimentally it has been found that this transition is not a sharp one and that log I_e departs from the straight line relation to V_s before space potential is reached. Thus, if this third method is used to determine space potential the value found will be low. The determinations made by the three methods are tabulated below. The space potentials are given with respect to the anode. Potentials with respect to the cathode may be obtained by adding the tube voltage, 32 volts, to the tabulated values. It is seen that the determinations made by the asymptote intersection method compare fairly well with those determined from the I_{sp} calculations, and are considered reasonably accurate. The asymptote intersection method is the preferred one because it is a simple graphical solution and requires no computations. All three methods gave positive values for the space potential, this being in agreement with the findings of Mahaffey when using a disc anode in mercury discharge (19).

Probe-Cath. Distance (mm)	I_{sp} (ma)	Space Pot. (intersection of asymptotes)	Space Pot. (from I_{sp})	Space Pot. (break in curve of log I_e-V_s)
2	2.1	+10.0 v.	+14.5 v.	+1.0 v.
4	1.43	7.0	8.5	3.0
6	2.04	5.5	6.5	3.0
8	1.69	5.0	5.0	3.0
10	1.44	6.5	6.0	4.0
12	1.76	4.5	4.0	3.0

Table 1. Space Potential With Respect to Anode

Maximum electron energy listed in Table 2 was determined by assuming it to be the voltage with respect to space at the point where the I_s^2 versus V_s curve departed from the straight-line portion of the curve when it was extrapolated toward increasing potential.

6. Conclusions.

The results of this work must be taken with reserve because of its limited scope. However, there is little doubt that oscillations of electrons and ions were present in the discharge plasma and that the frequencies observed can be attributed to these oscillations.

A comparison of measured oscillation intensity and calculated electron density is shown in Fig. 19. The electron density had a negative gradient in the 6-10 millimeter region. This was accompanied by an increase in oscillation intensity in the 8-10 millimeter region, culminating

[illegible]

[illegible]

[illegible]

with maximum intensity at the point where the density gradient changed sharply to a positive one. This was in accord with the theory advanced by Allis that oscillations are more likely to grow when a beam of electrons is moving down a plasma electron concentration gradient, and that the maximum intensity should occur at the end of a negative gradient [18]. It must be noted that data was obtained at relatively widely spaced points and that more data is necessary before a complete comparison of electron density and oscillation intensity can be made.

No apparent relationship could be found between space potential and oscillation intensity or electron distribution.

Observed frequencies of electron oscillations were lower than predicted maximum values by approximately a factor of two. It is possible that frequencies observed were subharmonics and that the fundamentals were above the ranges of the detection equipment. Because no meniscus or scattering was observed, it is concluded that oscillations were relatively weak. The reason for the absence of a meniscus is not known. It seems unlikely, but it may be that the emission properties of the Philips cathode are not conducive to the occurrence of such a phenomenon.

7. Recommendations.

a. Conduct further investigations of the plasma oscillations in the present configuration of the tube with various pressures, interelectrode distances, and type of gas. In particular, make intensive probe analyses,

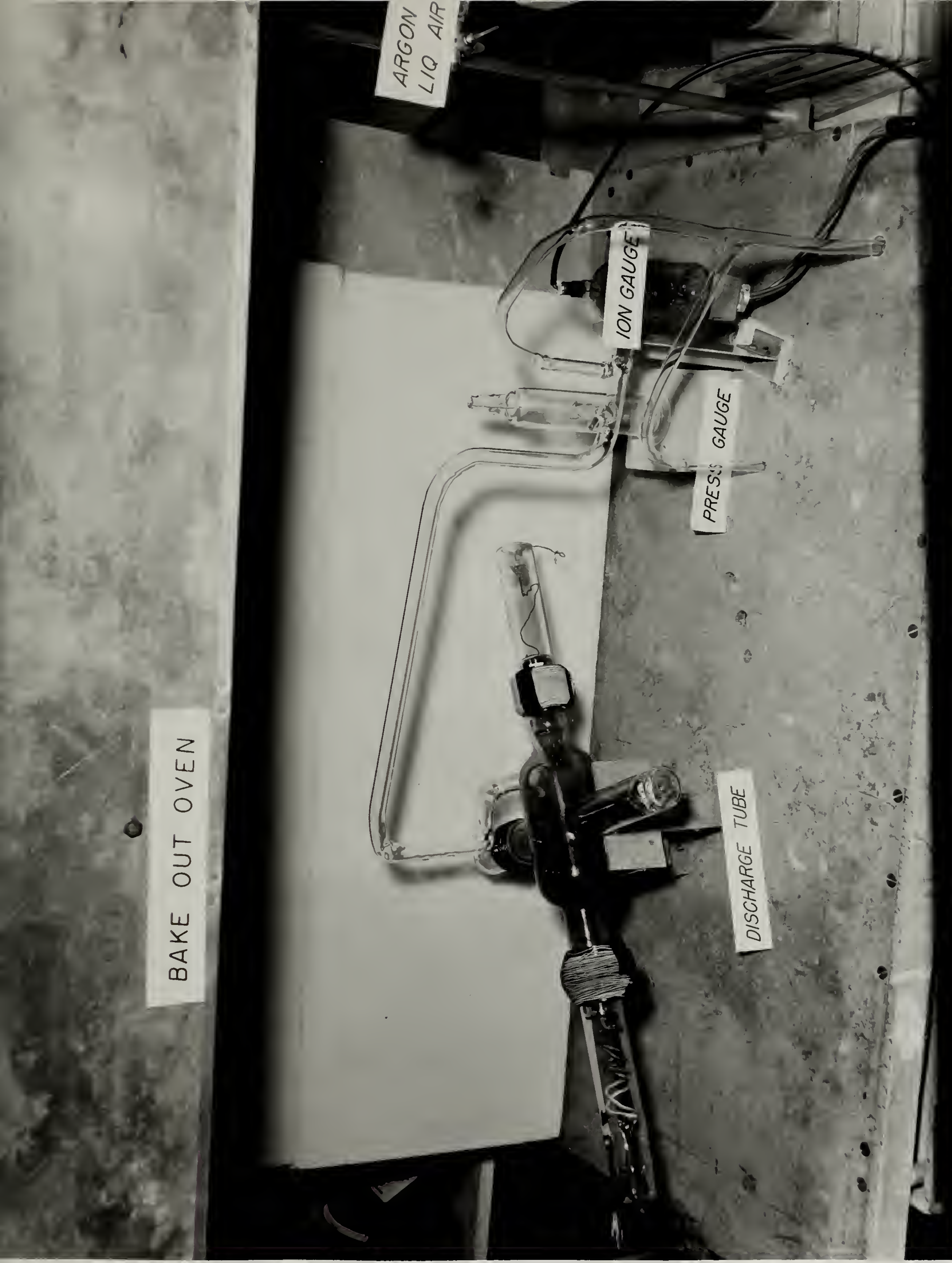
varying probe to cathode distances in steps not greater than 0.5 millimeters.

b. Obtain or design and construct sensitive frequency detection and measuring equipment with complete coverage up to about 2,000 megacycles.

c. Investigate the effects of a superimposed axial magnetic field on the plasma oscillations.

d. In order to reduce interference of the probe with the discharge and to obtain more reliable probe data, the wire probe should be replaced by a similar one of smaller diameter, e.g., one of diameter .004 inch as compared to the .008 inch diameter of the probe used.

e. Replace the ring probe with a small coil probe and investigate the magnetic field associated with the plasma.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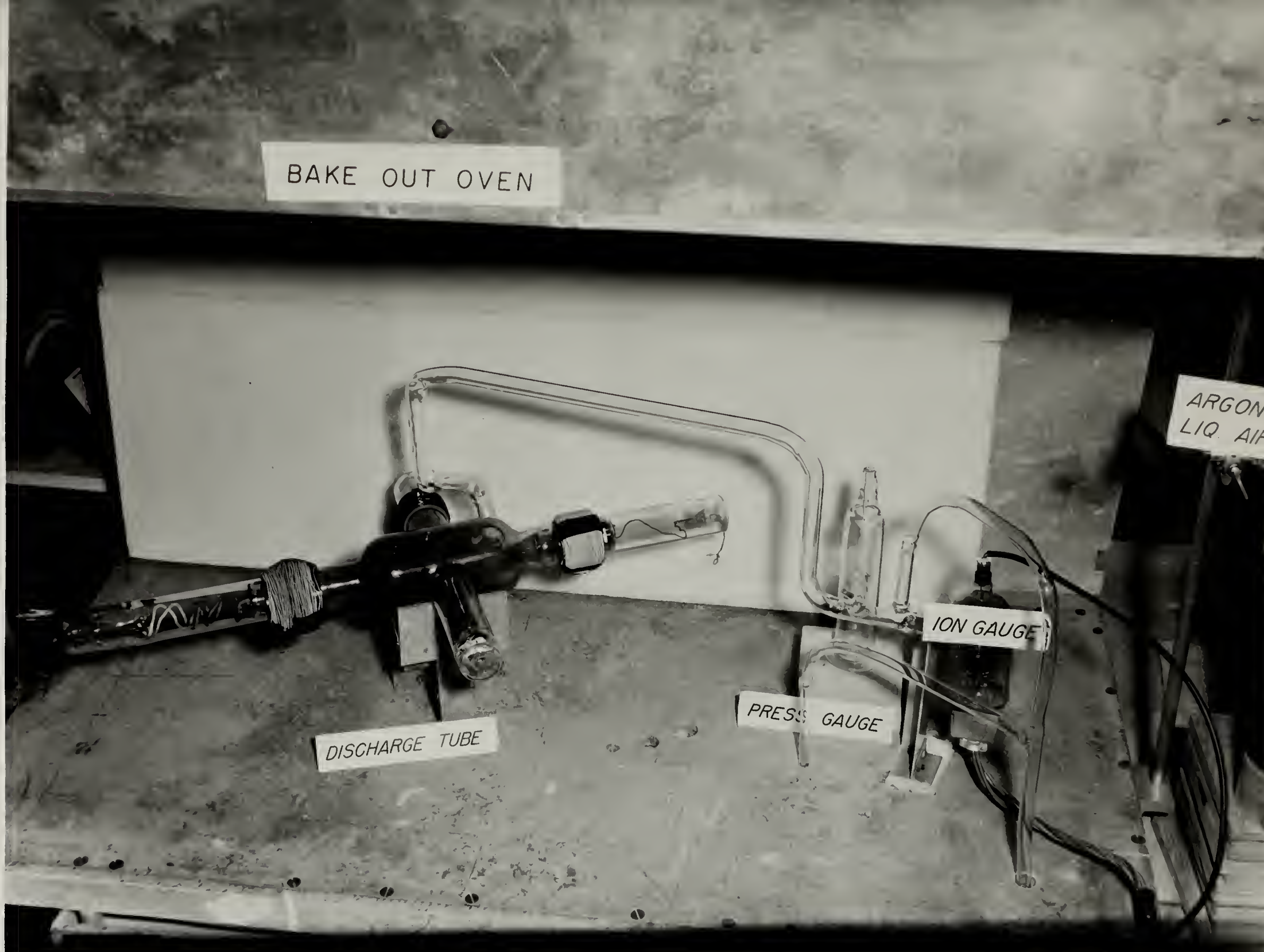
DISCHARGE TUBE
BAKE OUT OVEN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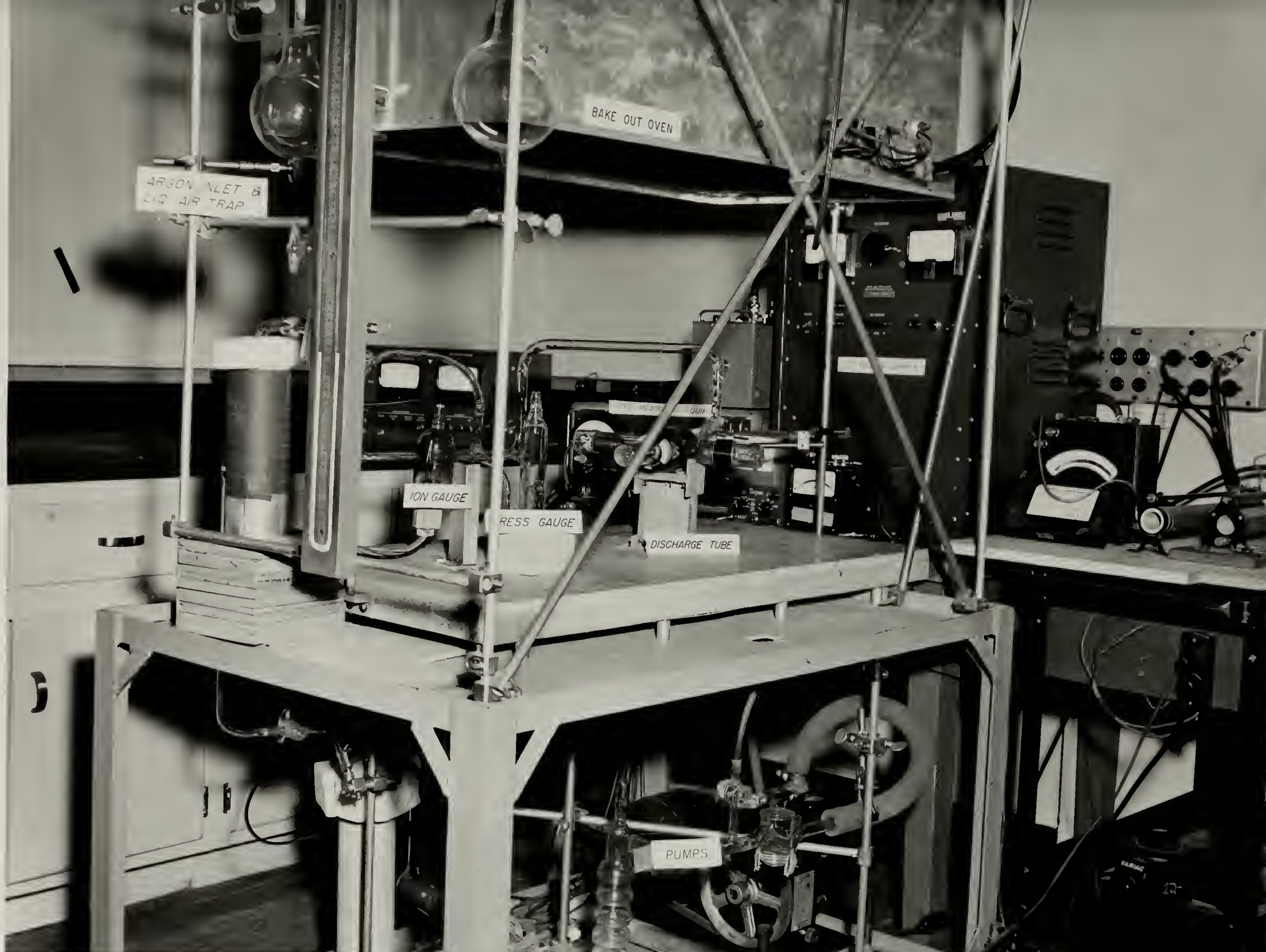
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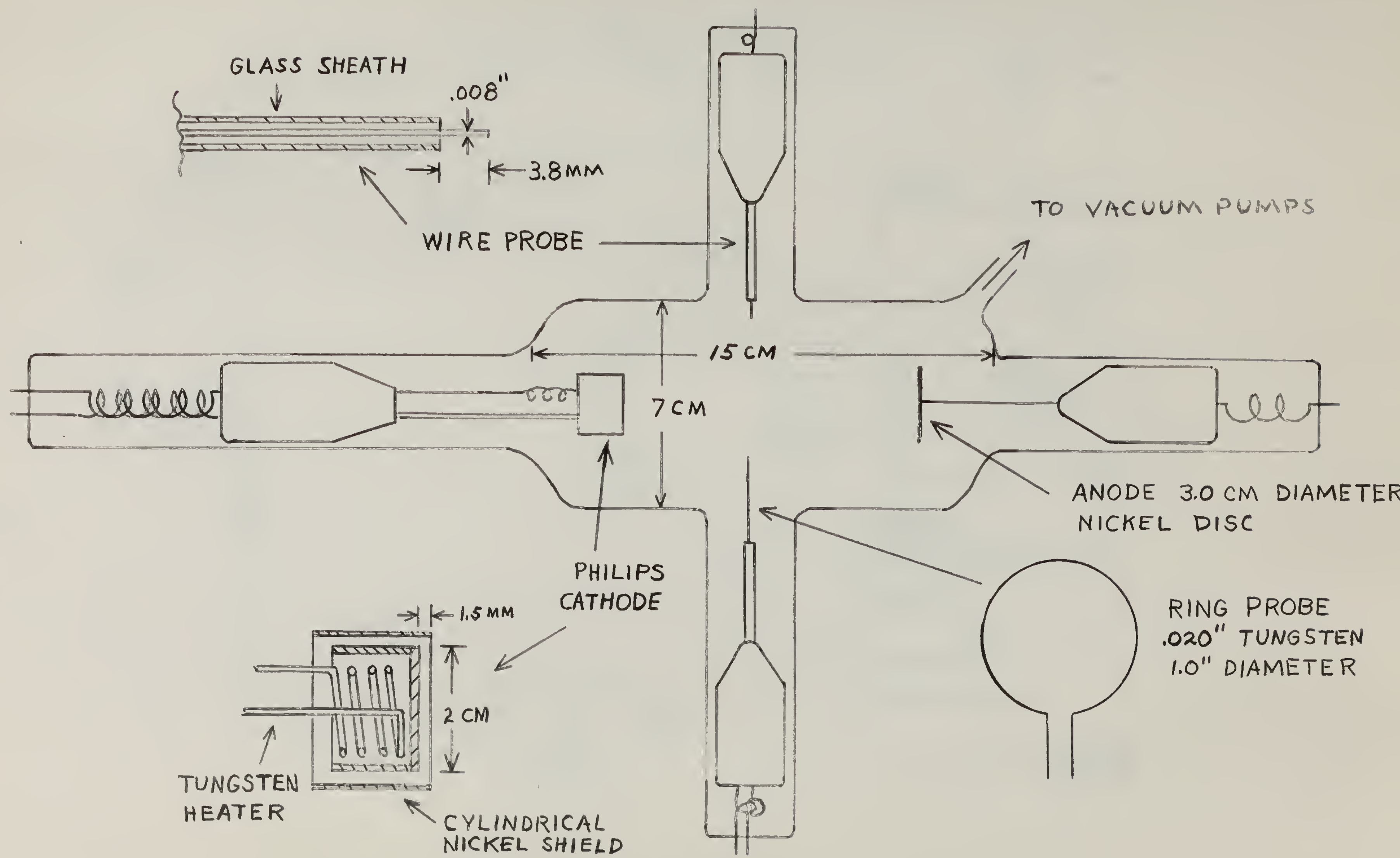


Fig. 3 - Discharge Tube

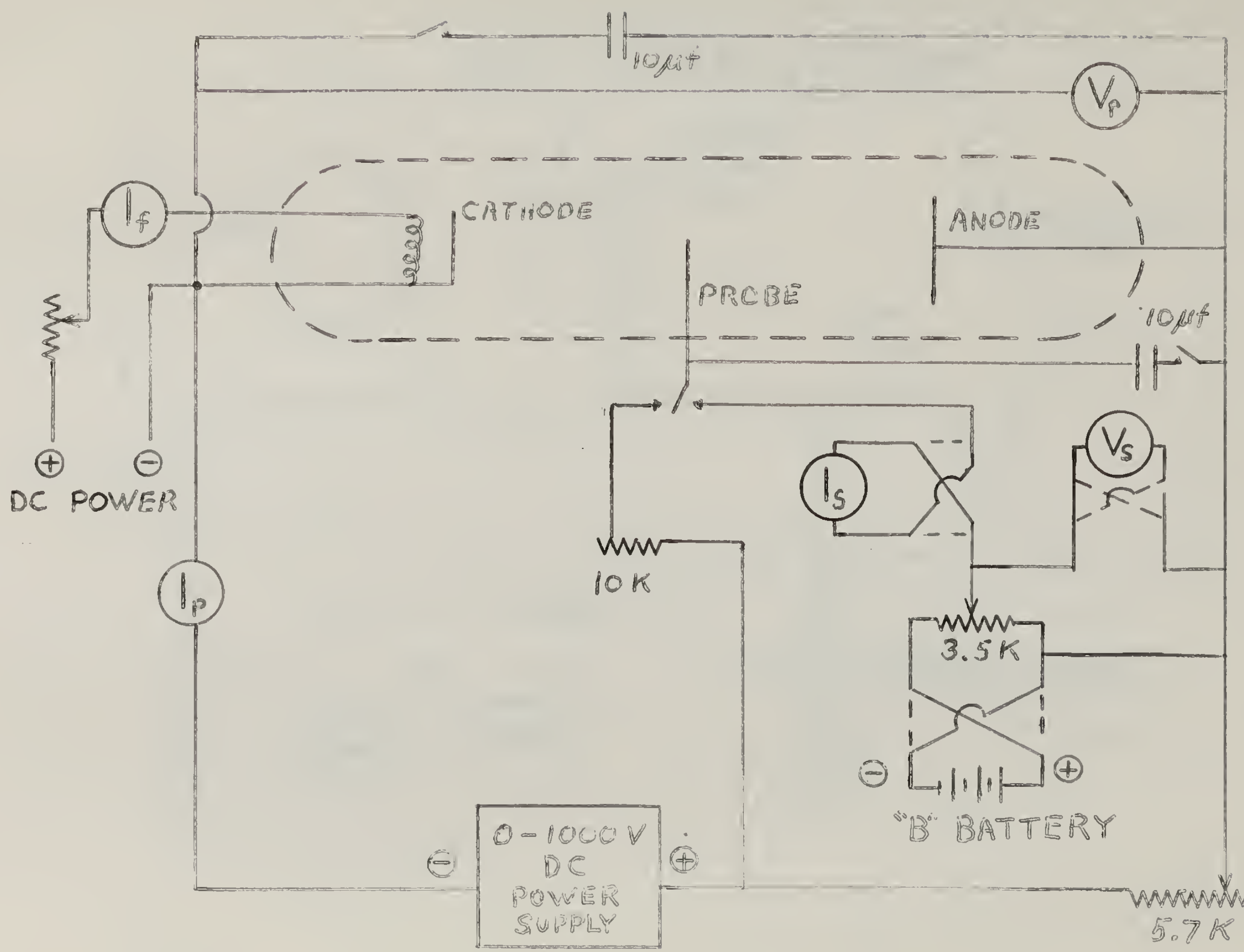


Fig. 4 - D. C. Circuitry

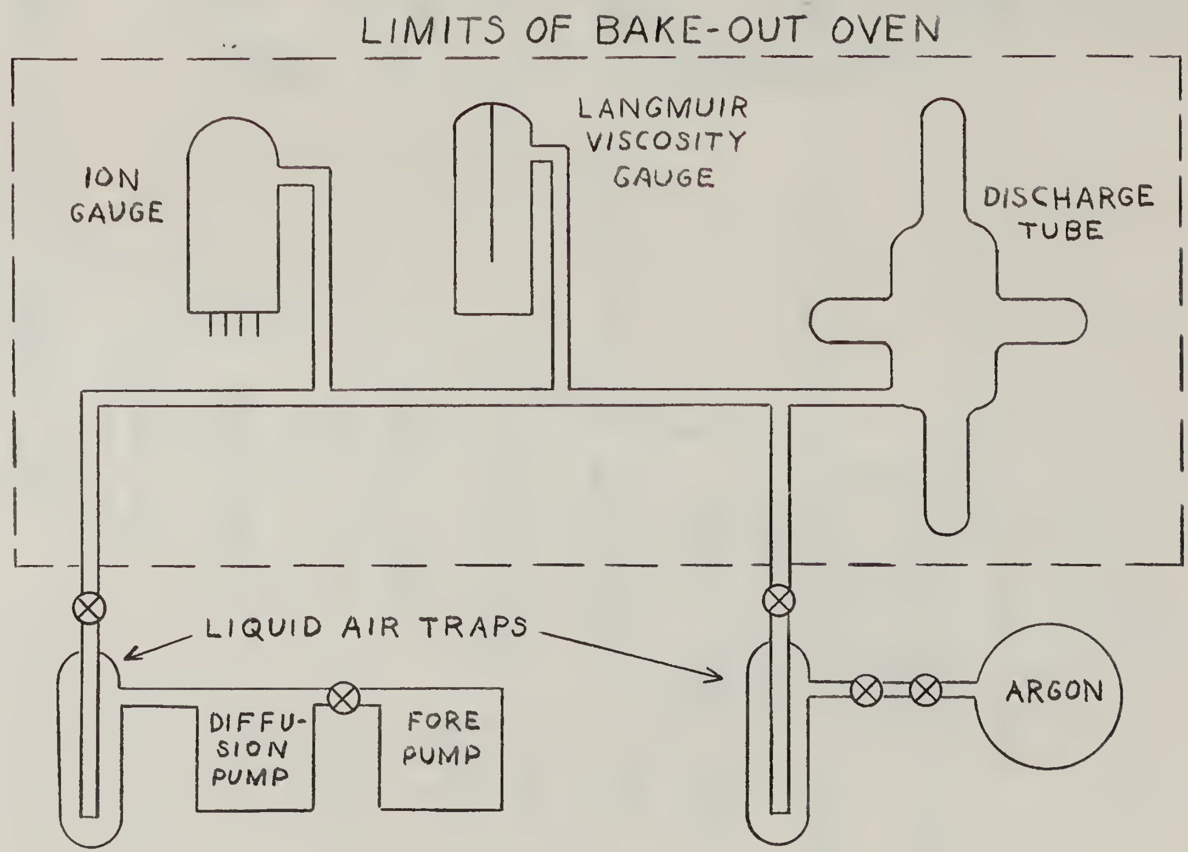


Fig. 5 - Schematic Diagram of Vacuum System

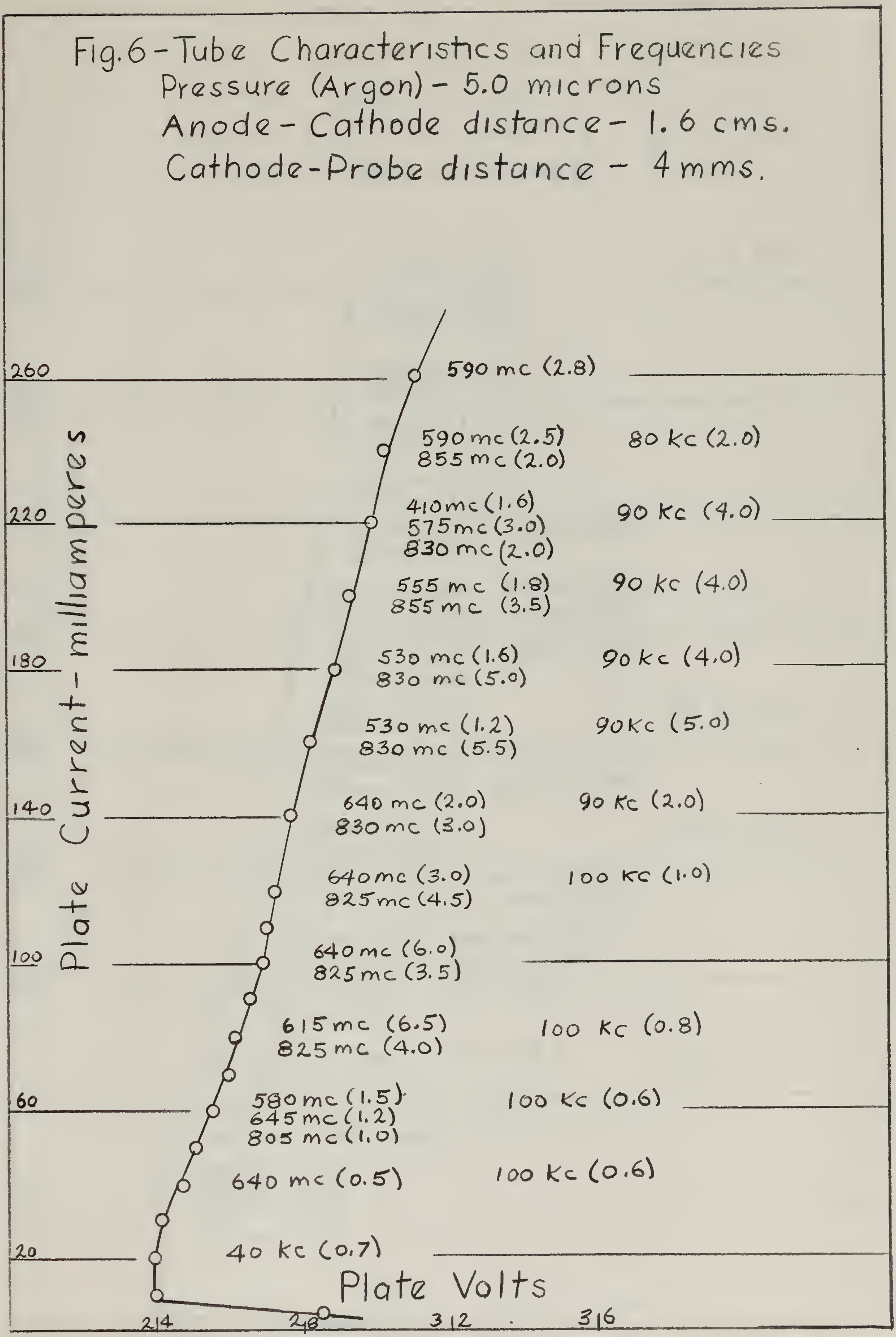
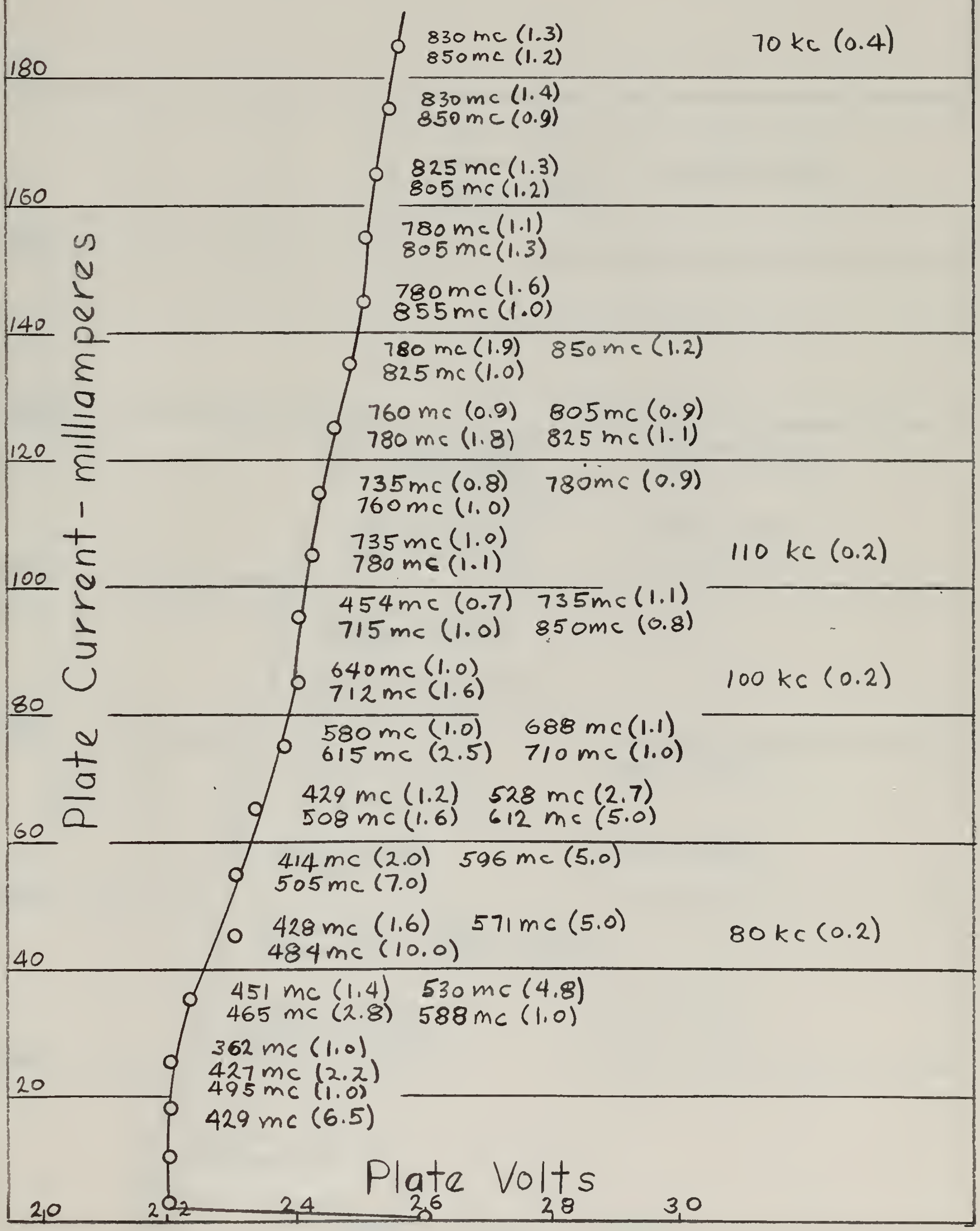


Fig.6-Tube Characteristics and Frequencies
Pressure (Argon) - 5.0 microns
Anode - Cathode distance - 1.6 cms.
Cathode-Probe distance - 4 mms.
260
220
180
140
100
60
20
Plate Current - milliamperes
590 mc (2.8)
590 mc (2.5)
855 mc (2.0)
80 kc (2.0)
410 mc (1.6)
575 mc (3.0)
830 mc (2.0)
90 kc (4.0)
555 mc (1.8)
855 mc (3.5)
90 kc (4.0)
530 mc (1.6)
830 mc (5.0)
90 kc (4.0)
530 mc (1.2)
830 mc (5.5)
90 kc (5.0)
640 mc (2.0)
830 mc (3.0)
90 kc (2.0)
640 mc (3.0)
825 mc (4.5)
100 kc (1.0)
640 mc (6.0)
825 mc (3.5)
615 mc (6.5)
825 mc (4.0)
100 kc (0.8)
580 mc (1.5)
645 mc (1.2)
805 mc (1.0)
100 kc (0.6)
640 mc (0.5)
100 kc (0.6)
40 kc (0.7)
Plate Volts
214
248
312
316

Fig. 7 - Tube Characteristics and Frequencies
Pressure (Argon) - 5.0 microns
Anode-Cathode distance - 1.6 cms.
Cathode-Probe distance - 5 mms.



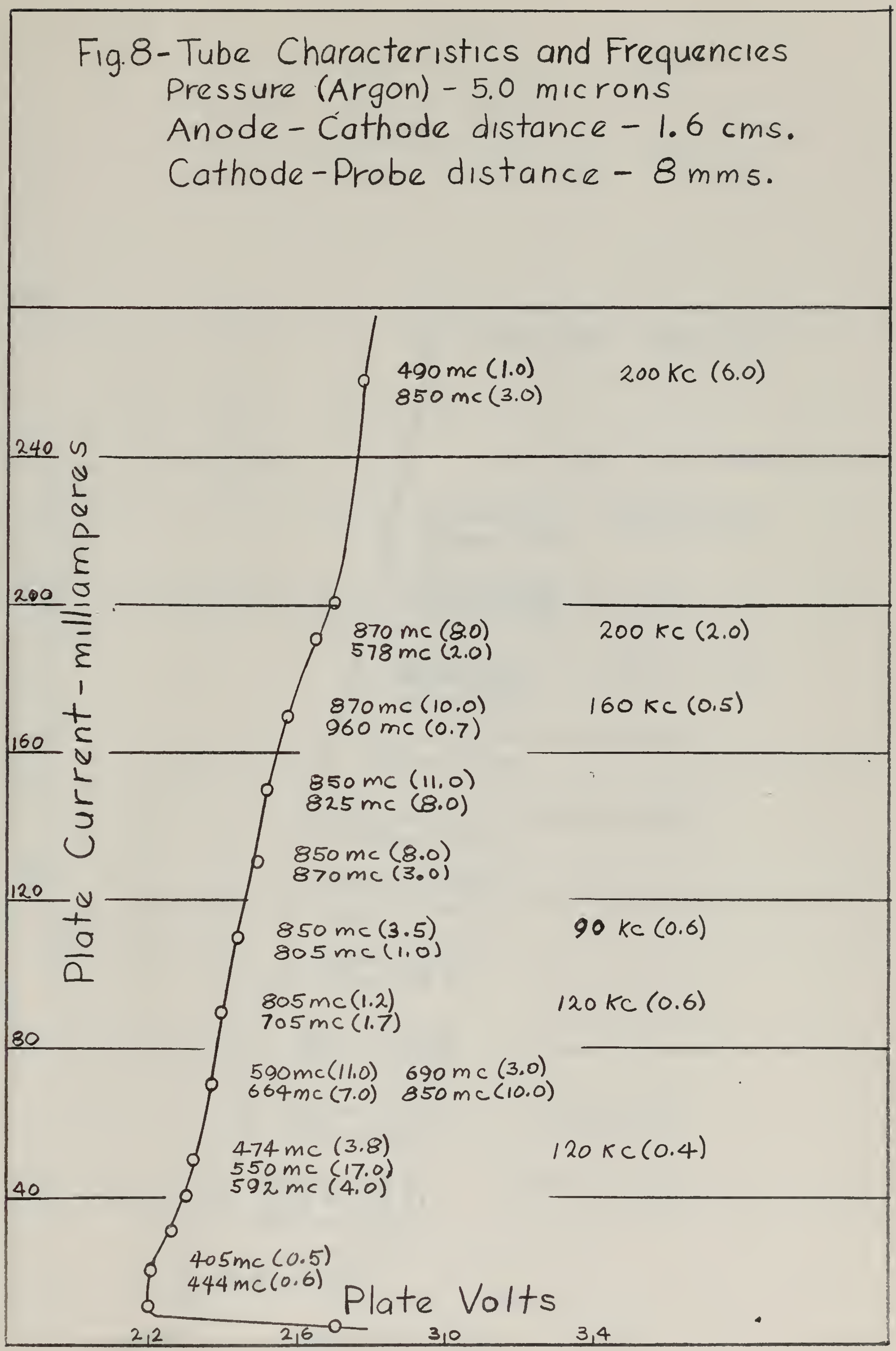


Fig. 8 - Tube Characteristics and Frequencies
Pressure (Argon) - 5.0 microns
Anode - Cathode distance - 1.6 cms.
Cathode - Probe distance - 8 mms.
Plate Current - milliamperes
Plate Volts
240
200
160
120
80
40
2.2
2.6
3.0
3.4
490 mc (1.0)
850 mc (3.0)
200 Kc (6.0)
870 mc (8.0)
578 mc (2.0)
200 Kc (2.0)
870 mc (10.0)
960 mc (0.7)
160 Kc (0.5)
850 mc (11.0)
825 mc (8.0)
850 mc (8.0)
870 mc (3.0)
850 mc (3.5)
805 mc (1.0)
90 Kc (0.6)
805 mc (1.2)
705 mc (1.7)
120 Kc (0.6)
590 mc (11.0)
664 mc (7.0)
690 mc (3.0)
850 mc (10.0)
474 mc (3.8)
550 mc (17.0)
592 mc (4.0)
120 Kc (0.4)
405 mc (0.5)
444 mc (0.6)

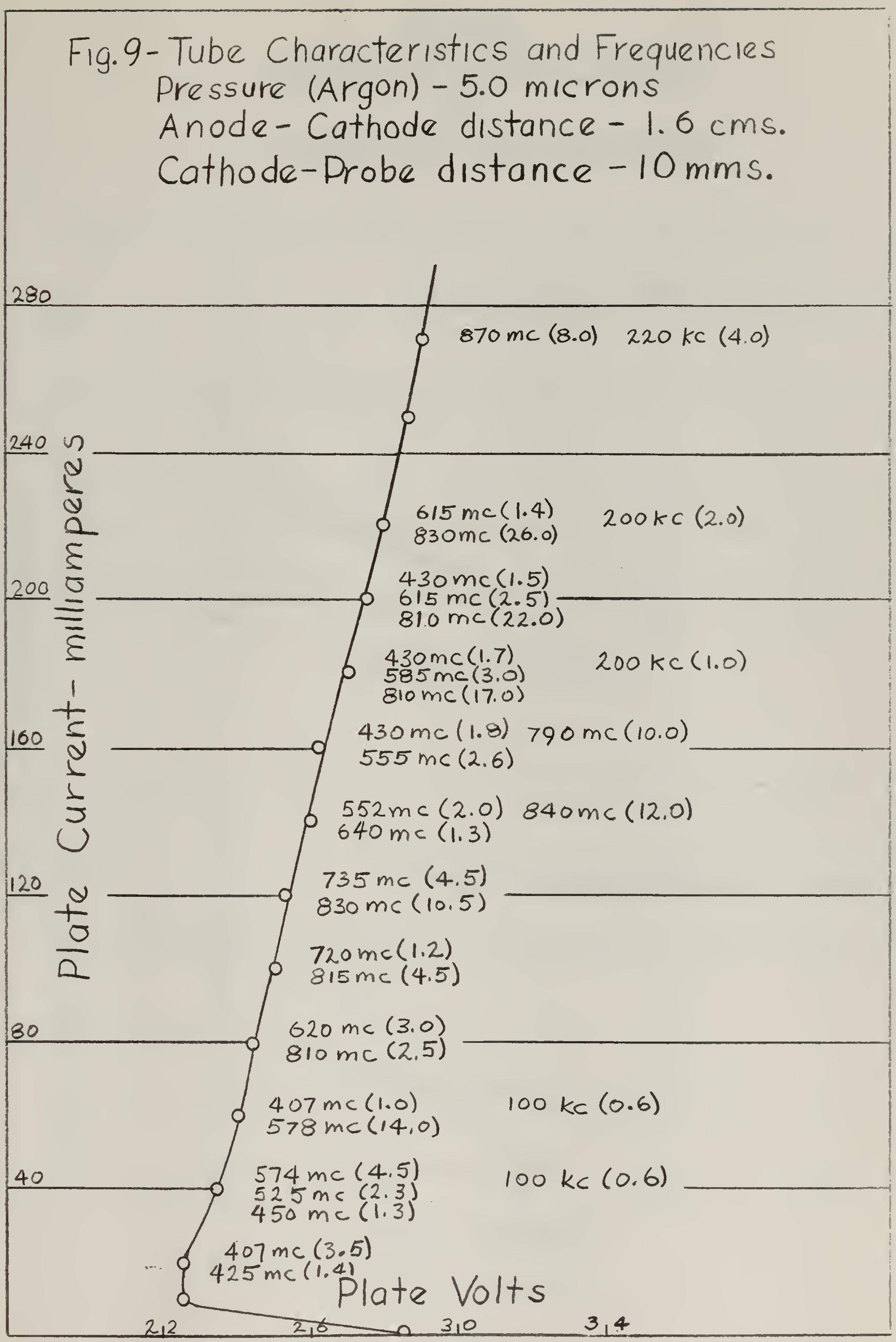


Fig. 9 - Tube Characteristics and Frequencies
Pressure (Argon) - 5.0 microns
Anode - Cathode distance - 1.6 cms.
Cathode-Probe distance - 10 mms.
Plate Current - milliamperes
Plate Volts
280
240
200
160
120
80
40
212
216
310
314
870 mc (8.0) 220 kc (4.0)
615 mc (1.4)
830 mc (26.0)
200 kc (2.0)
430 mc (1.5)
615 mc (2.5)
810 mc (22.0)
430 mc (1.7)
585 mc (3.0)
810 mc (17.0)
200 kc (1.0)
430 mc (1.8) 790 mc (10.0)
555 mc (2.6)
552 mc (2.0) 840 mc (12.0)
640 mc (1.3)
735 mc (4.5)
830 mc (10.5)
720 mc (1.2)
815 mc (4.5)
620 mc (3.0)
810 mc (2.5)
407 mc (1.0)
578 mc (14.0)
100 kc (0.6)
574 mc (4.5)
525 mc (2.3)
450 mc (1.3)
100 kc (0.6)
407 mc (3.5)
425 mc (1.4)

Fig. 10
Square of Probe Current
vs.
Probe Voltage wrt Anode

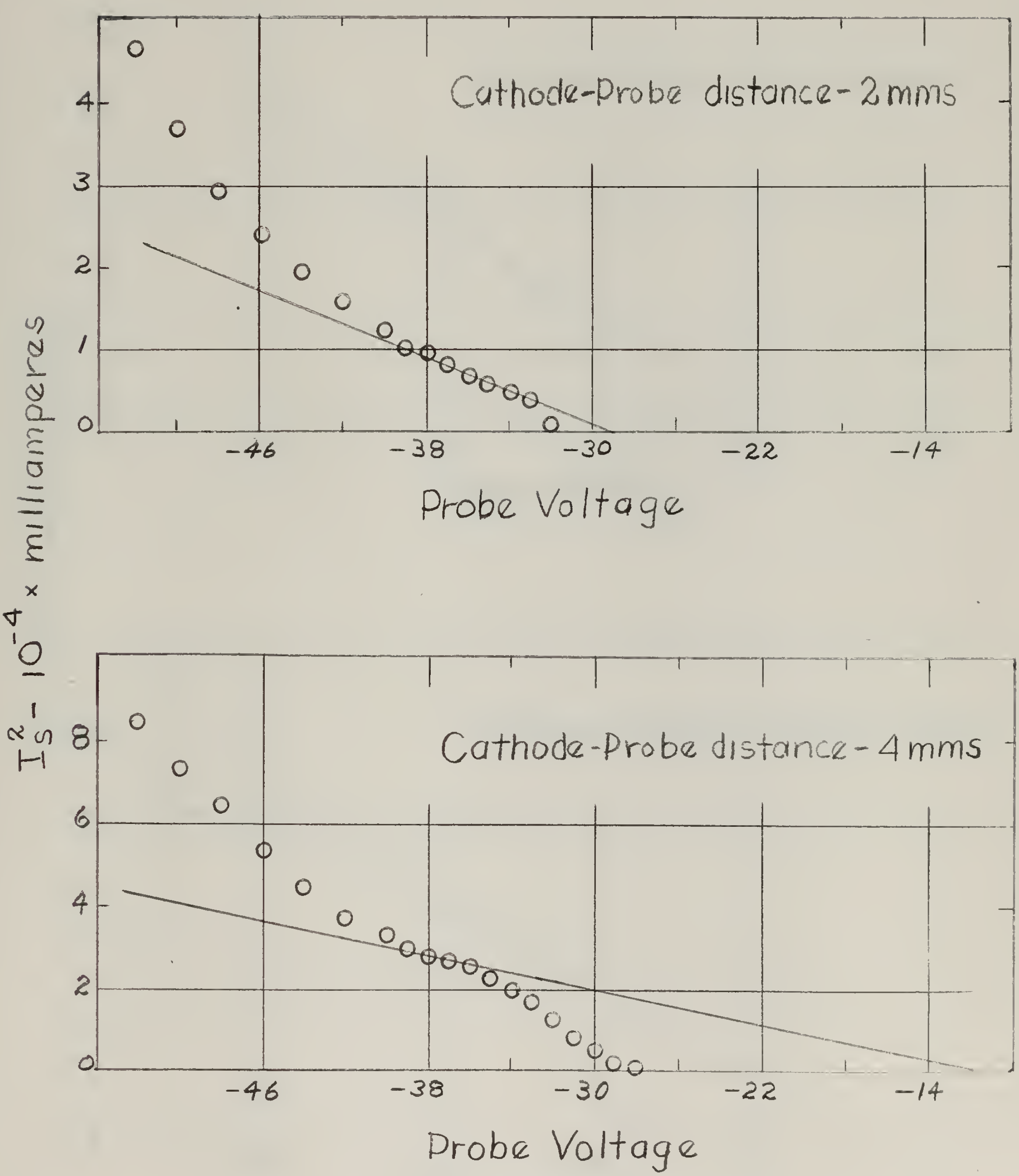


Fig. 11
Square of Probe Current
vs.
Probe Voltage wrt Anode

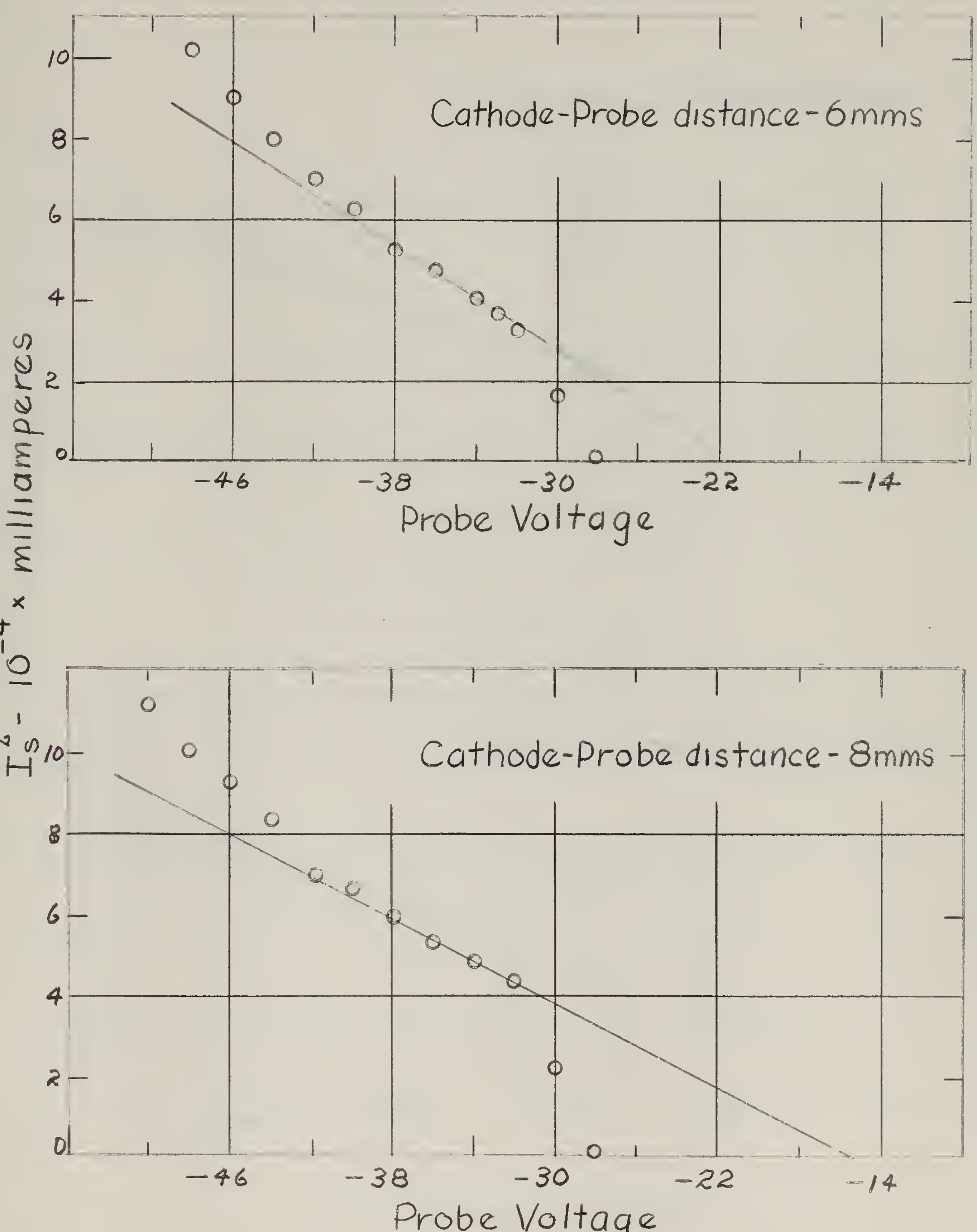
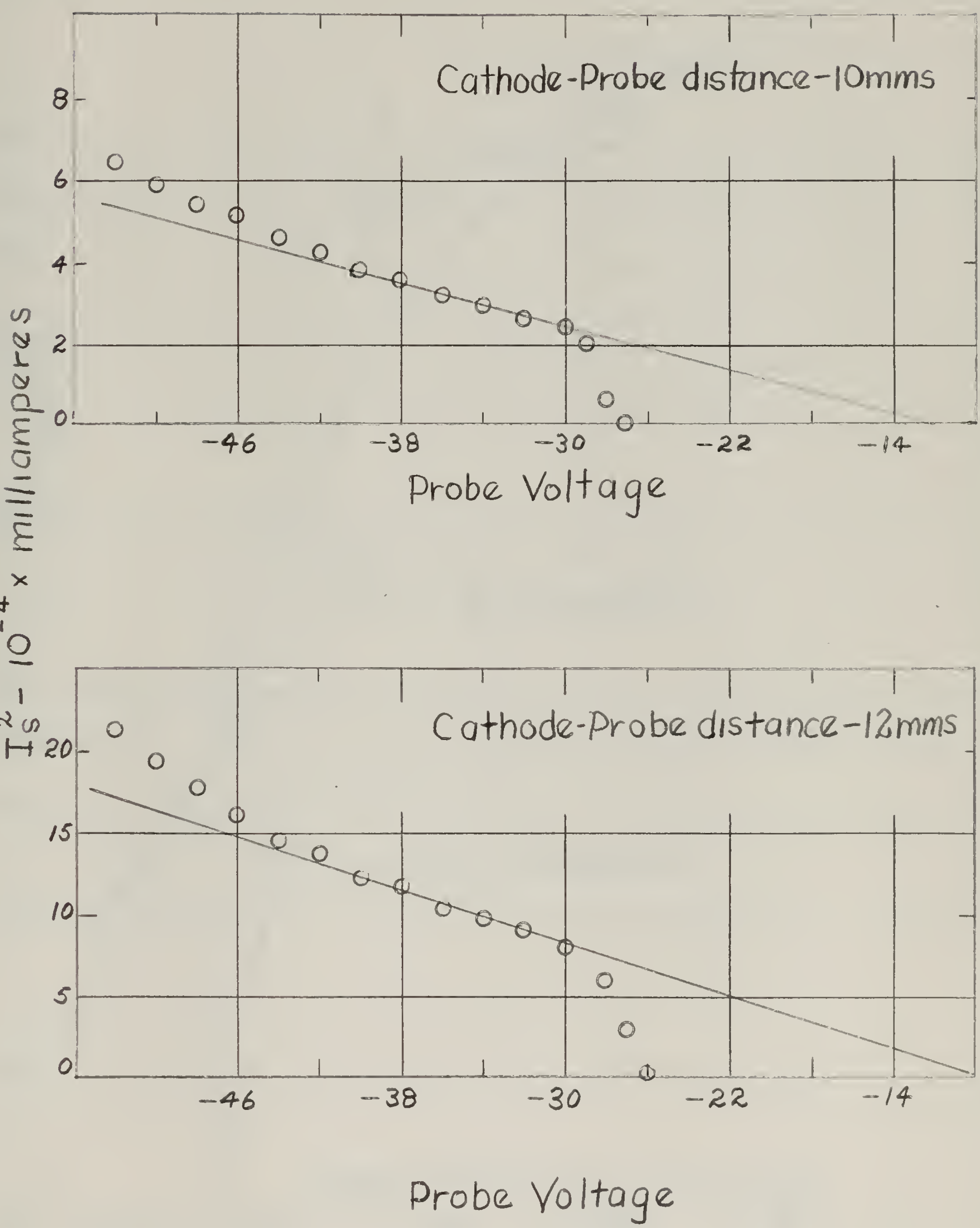


Fig. 12
Square of Probe Current
vs.
Probe Voltage wrt Anode



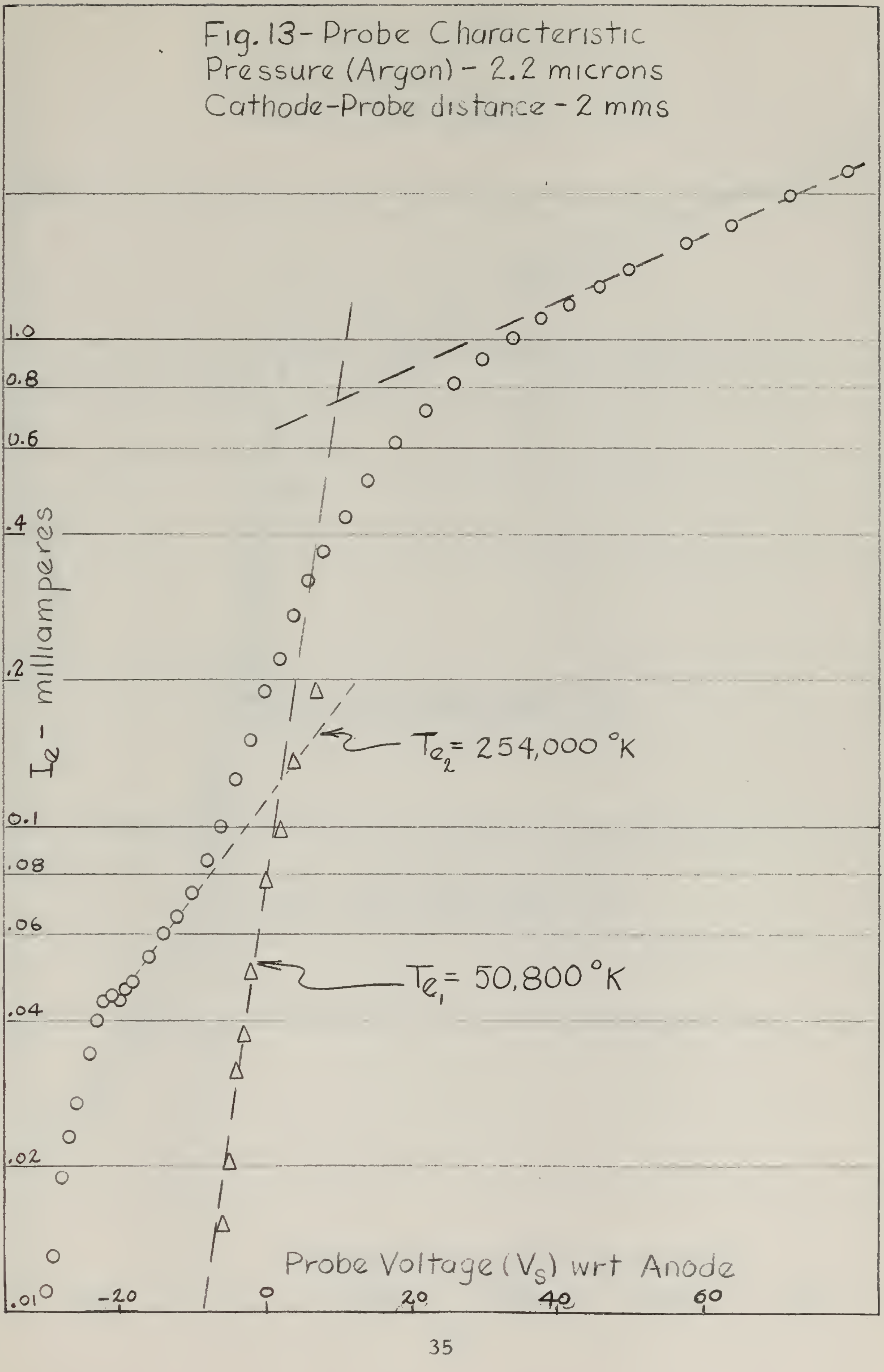


Fig. 13 - Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 2 mms
1.0
0.8
0.6
.4
.2
0.1
.08
.06
.04
.02
.01
I_e - milliamperes
T_{e_2} = 254,000 °K
T_{e_1} = 50,800 °K
Probe Voltage (V_s) wrt Anode
-20
0
20
40
60

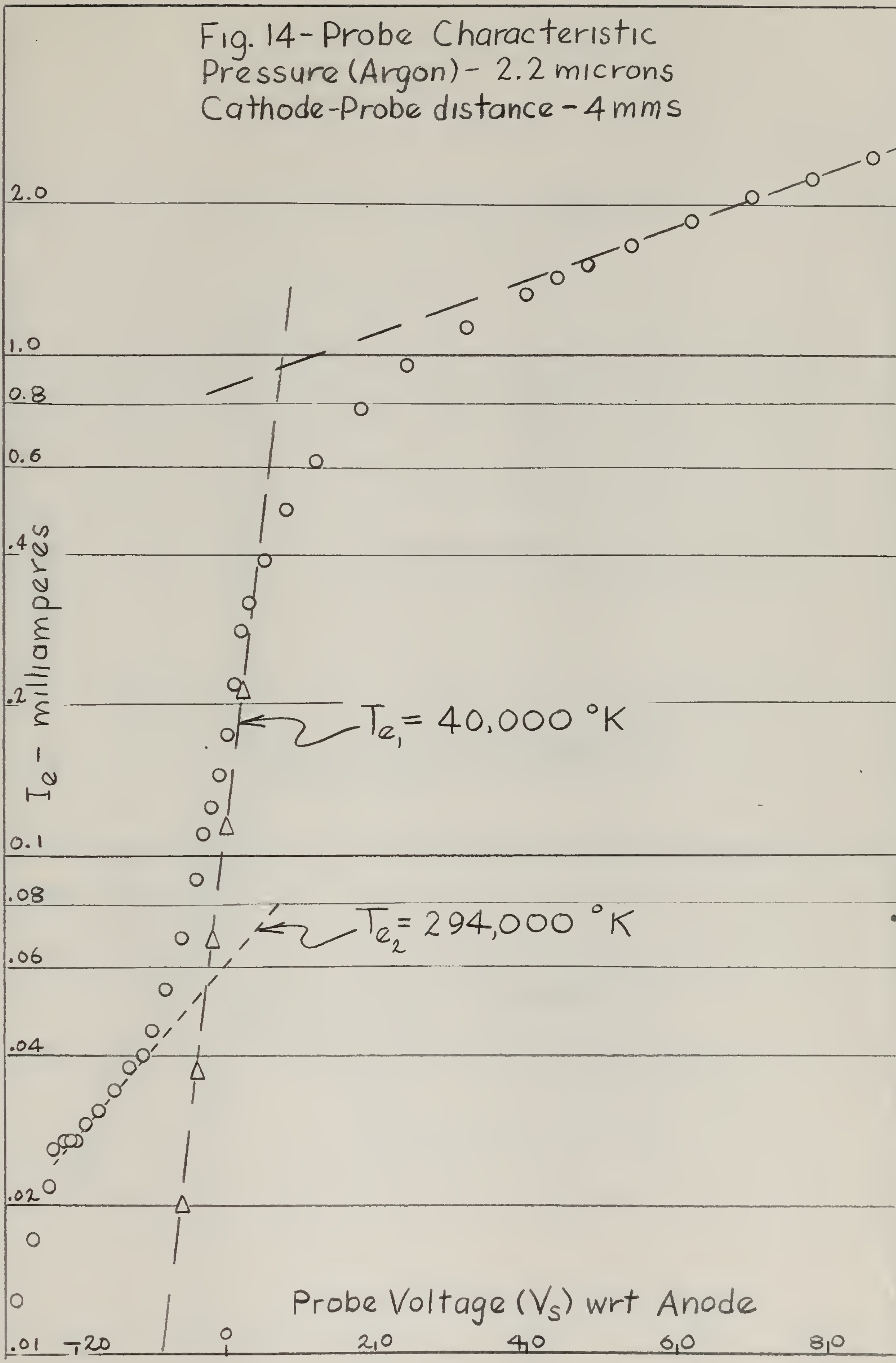


Fig. 14 - Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 4 mms

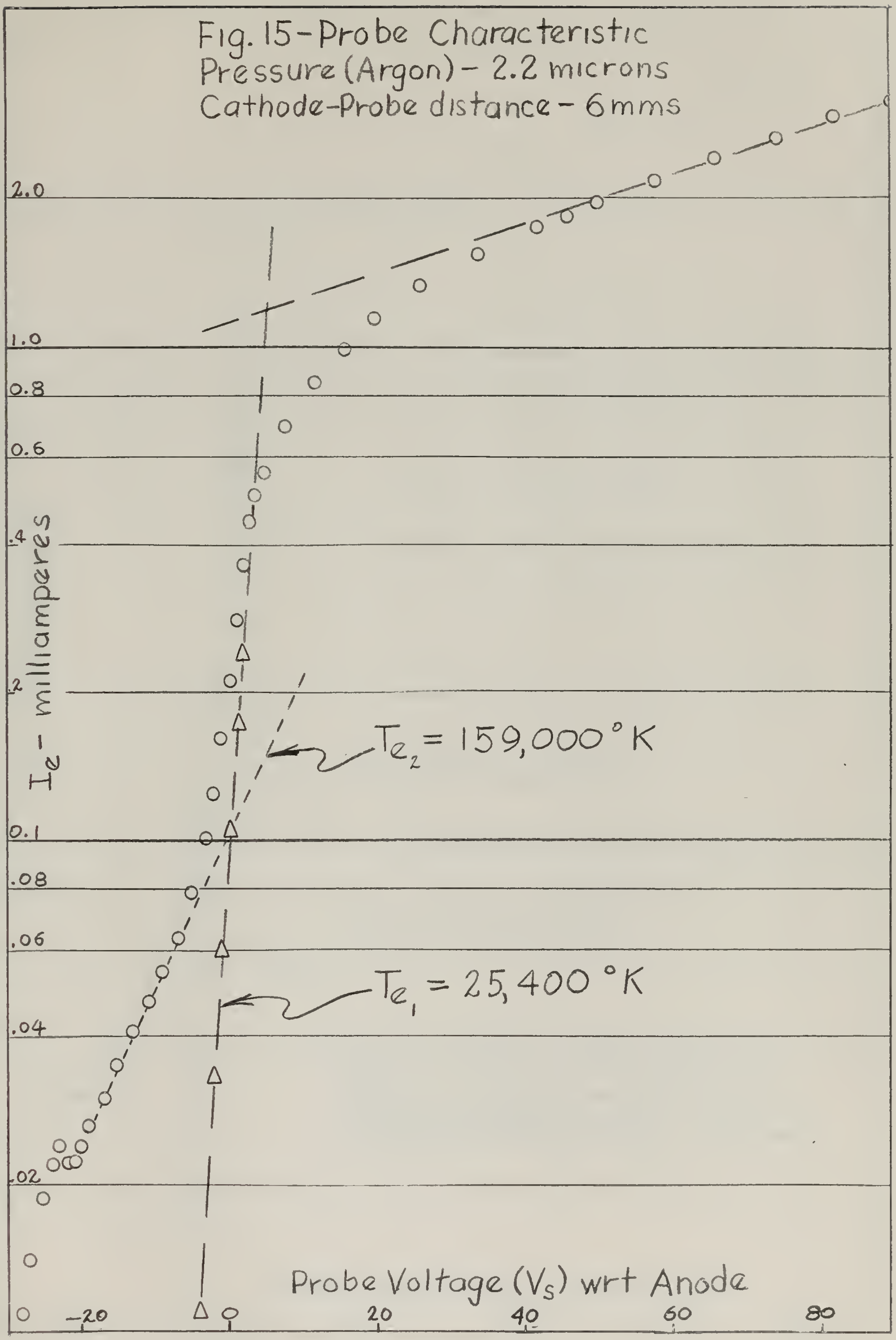


Fig. 15-Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 6 mms
2.0
1.0
0.8
0.6
.4
.2
0.1
.08
.06
.04
.02
I_e - milliamperes
T_{e_2} = 159,000 °K
T_{e_1} = 25,400 °K
Probe Voltage (V_s) wrt Anode
-20
0
20
40
60
80

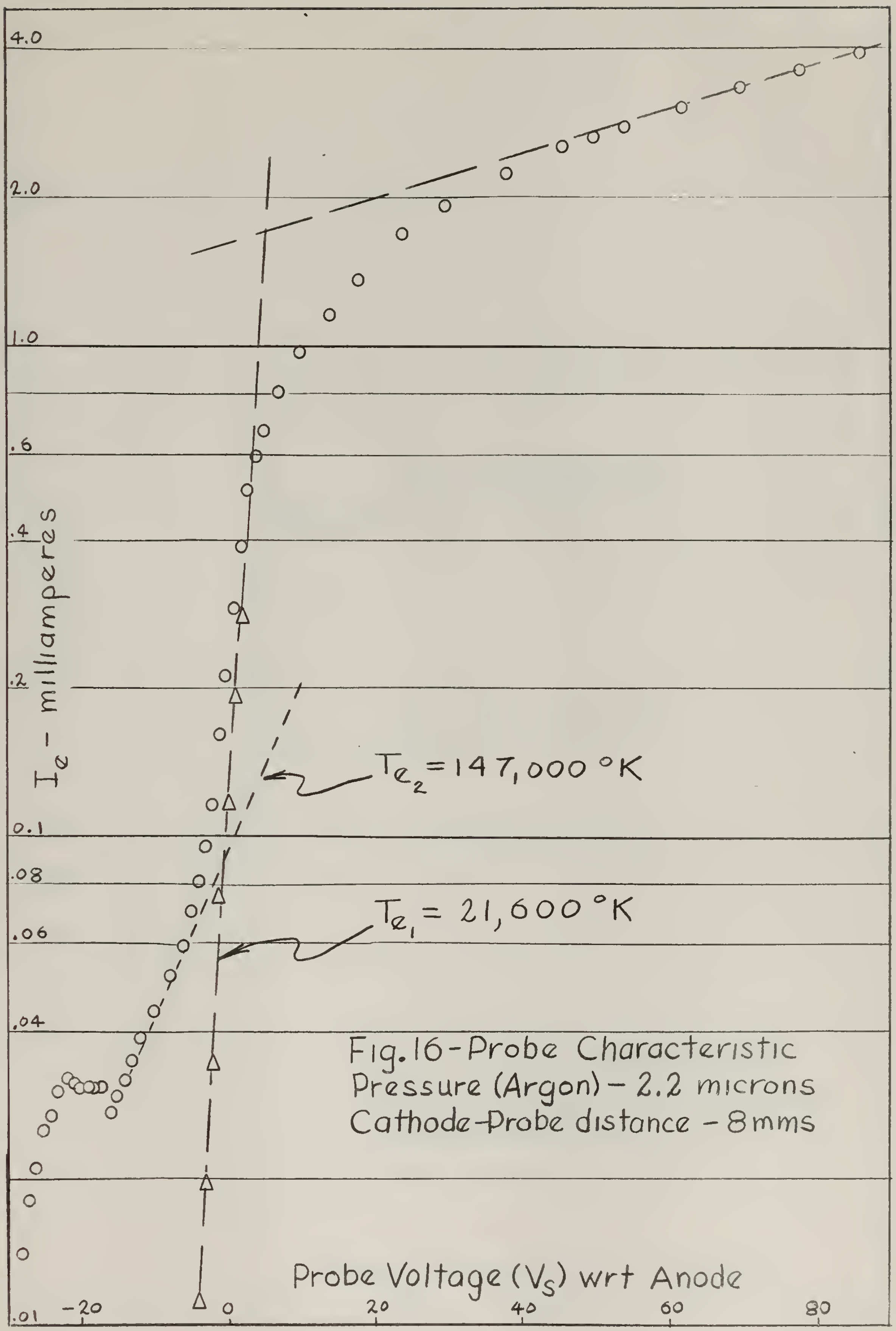


Fig. 16 - Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 8 mms

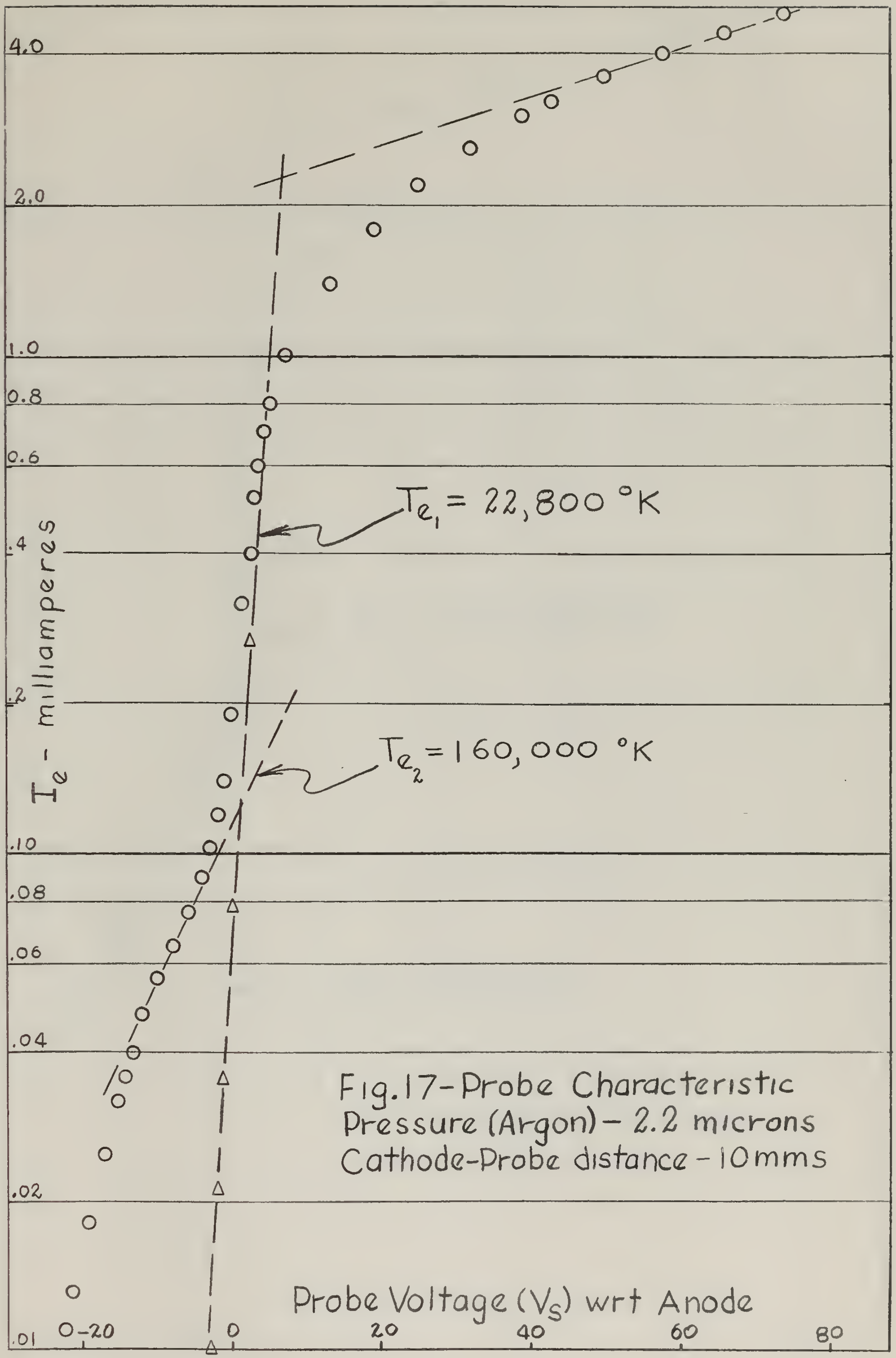


Fig.17-Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 10mms

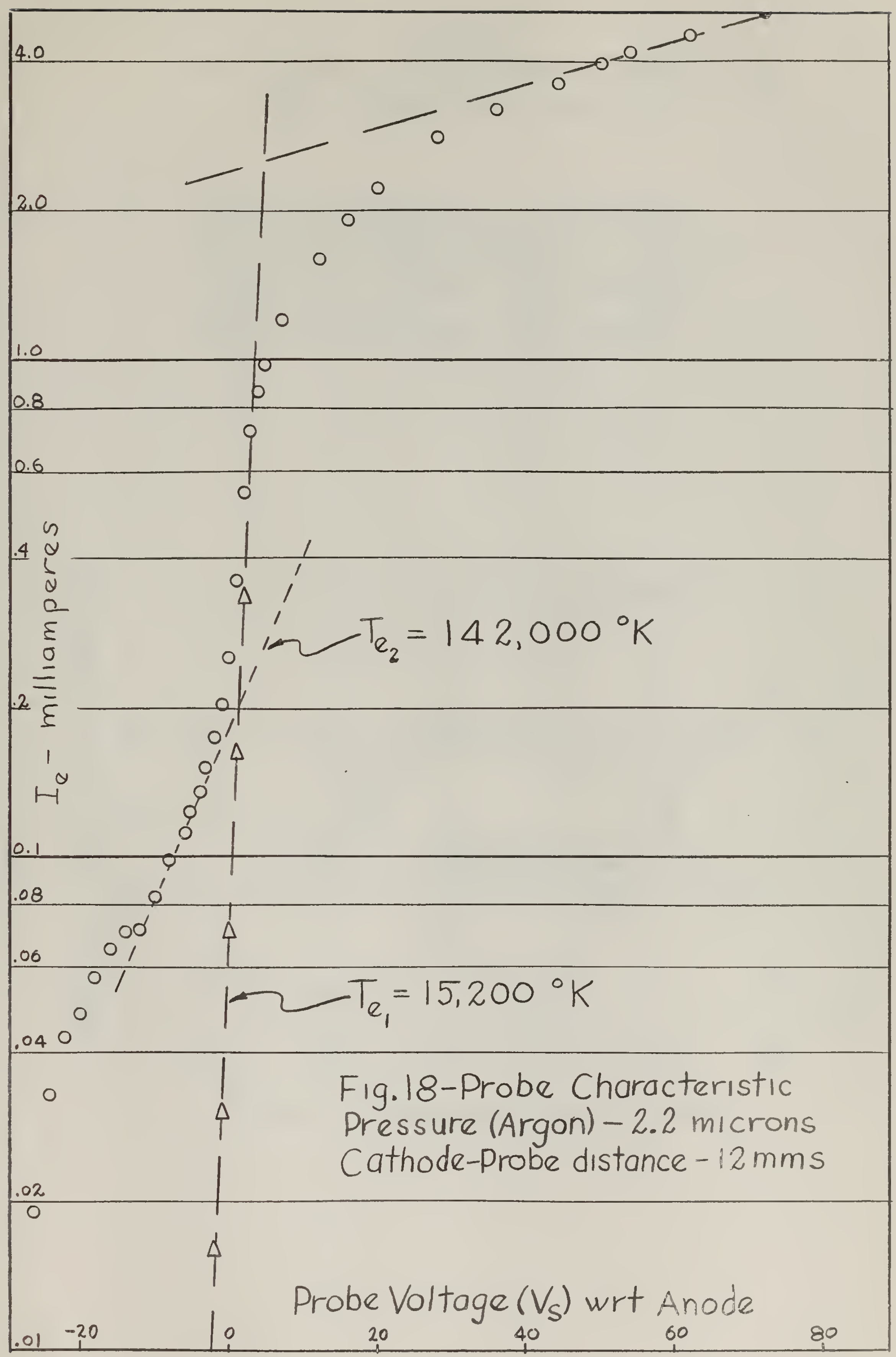


Fig. 18-Probe Characteristic
Pressure (Argon) - 2.2 microns
Cathode-Probe distance - 12 mms

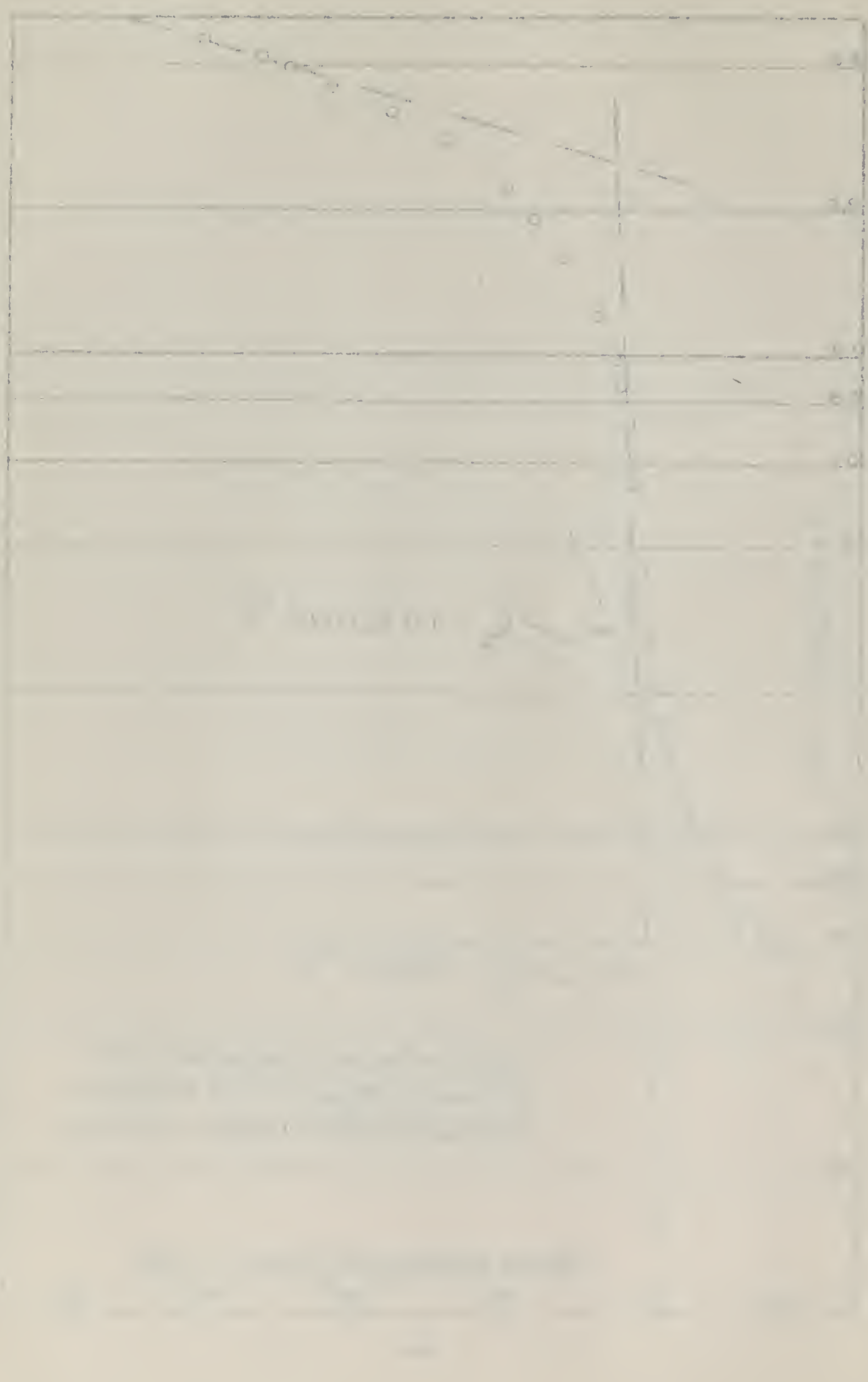
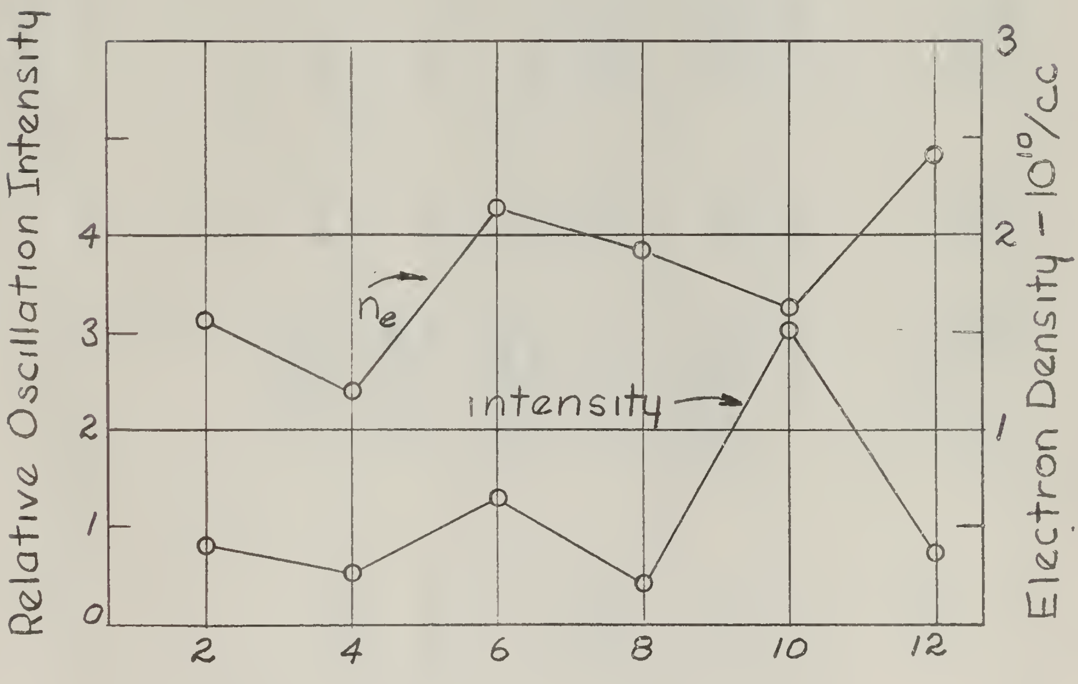


Fig. 19
Correlation of Oscillation Intensity and Electron Density

Pressure (Argon) - 2.2 microns
Anode - Cathode distance - 1.5 cms
Plate Current - 50 mamps.
Plate Voltage - 32 volts



Probe to Cathode Distance (mm)	Space Potential wrt anode (volts)	Maximum Electron Energy (volts)	Electron Density $10^{10}/cc$	Electron Temp. (^{o}K)	Electron Osc. Freq Calc. (mc)	Obs. (mc) (relative-intensity)	Pos. Ion Osc. Freq Calc. (kc)	Obs (kc)	Fig.
2	+ 10.0	- 43	1.56	50,800	1100	605(0.8)	4100	530	10, 13
4	7.0	43	1.20	40,000	980	520(0.35) 610(0.5)	3600	--	10, 14
6	5.5	37.5	2.15	25,400	1310	610(1.3)	4900	--	11, 15
8	5.0	37	1.93	21,600	1250	530(0.6) 608(0.4)	4600	--	11, 16
10	6.5	36.5	1.60	22,800	1130	600(2.6) 800(3.0)	4200	--	12, 17
12	4.5	34.5	2.40	15,200	1390	505(0.7) 585(0.7)	5100	--	12, 18

Plate Voltage - 32 volts

Plate Current - 50 milliamperes

Tube Pressure (Argon) - 2.2 microns

Cathode-Anode Distance - 1.5 centimeters

Summary of Probe Analysis

Table 2

42

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