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THE CONSTRUCTION AND GENERAL PROPERTIES OF A BRUSH CATHODE DISCHARGE

BY

JOSEPH P. BINGHAM

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APPROVAL SHEET

Title of Thesis: The Construction and General Properties
of a Brush Cathode Discharge

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ABSTRACT

Title of Thesis: The Construction and General Properties of
a Brush Cathode Discharge

Joseph Peter Bingham, Master of Science, 1968

Thesis directed by: R. T. Bettinger, Assistant Professor of Physics

The use of a brush cathode in a DC glow discharge allows stable operation in the abnormal glow region. In a strongly abnormal glow discharge, the negative glow becomes quite extensive, and is useful as a laboratory plasma.

A brush cathode DC glow discharge tube, 6" in diameter and 24" in length, was constructed for the present experiment. The tube operated stably in the abnormal glow region and large negative glows were produced. Langmuir probe studies of the negative glow plasma at pressures less than 400 μ and discharge currents less than 2 ma yielded electron temperatures and densities of about $700^{o}K$ and 10^8/cc respectively. At greater discharge currents and pressures, the Langmuir probe measurements were unreproducible, probably because condensable vapor impurities formed a surface film on the probe. Such a film could cause a change in the probe contact potential and thus affect the probe characteristics.

THE CONSTRUCTION AND GENERAL PROPERTIES OF A BRUSH CATHODE DISCHARGE

BY

Joseph P. Bingham

August 1967

Thesis submitted to the Faculty of the
Graduate School of the University
of Maryland in partial fulfillment of
the requirements for the degree of
Master of Science
1968

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FIGURE CAPTIONS

INTRODUCTION

There exists in the laboratory the need for a convenient source of plasma with low electron temperatures (1000°K) and with density adjustable over a wide range. The negative glow region of the DC glow discharge is such a plasma, but the discharge must be strongly "abnormal" if the size of the negative glow is to be sufficient for laboratory use. Abnormal discharges using disc shaped cathodes are very unstable and go over to an arc very easily. With a brush cathode, however, the abnormal glow discharge is very stable so that large negative glows can be easily generated.

In the present experiment, a six inch diameter brush cathode was constructed and used in a helium DC glow discharge, and the properties of the large negative glow generated were studied.

CHAPTER I

THE GLOW DISCHARGE

When a sufficiently high potential is applied between two electrodes in a tube whose contents are at atmospheric pressure, a thin rapidly moving spark will appear between the two electrodes. As the pressure in the tube is reduced, the spark will become more diffuse, until, at a pressure of about five torr, the discharge will nearly fill the tube, and will demonstrate some striations. Such a discharge is called a glow discharge. As the pressure is further reduced, the striations will expand and separate. Such a discharge, at a pressure of about one half torr, is illustrated in Fig. 1. Proceeding from the cathode, the striations are known as the Aston dark space, the cathode glow, the cathode dark space, the negative glow, the Faraday dark space, the positive column, the anode dark space, and finally, the anode glow.

Several methods have evolved for the measurement of electric field strength in a discharge. They include probe measurements, measurements of Stark effect splitting of spectral lines (BROSE, 1919), and measurement of the transverse deflection of a fine pencil of fast electrons by the field (ASTON, 1911).

Measurements using these methods have given us the electric field and potential distribution in a glow discharge illustrated in Fig. 2. It is seen that the electric field decreases approximately linearly in the cathode dark space, and that nearly the full potential across the tube is present between the cathode and the inner border of the negative glow. This potential drop is known as the cathode fall or cathode drop. Because the electric field decreases almost linearly in the cathode dark space, we can write

$$E = C(D - X)$$

where

E is the electric field intensity

C is a constant

D is the length of the cathode dark space

X is the distance from the cathode

Now, from Poisson's equation

$$\frac{dE}{dX} = -4\pi\rho$$

or $$C = 4\pi\rho$$

where ρ is the space charge density. That is, there is a uniform positive ion space charge distribution in the cathode dark space. Because the cathode dark space is a region of high positive ion concentration and high field strength, the positive ions are accelerated towards the cathode and constantly bombard it while the electrons emitted from the cathode are accelerated towards the negative glow.

Brewer and Westhaver (1937) found a definite correlation between the length of the negative glow and the range of electrons that have been accelerated by a potential difference equal to the cathode fall (see Fig. 3). The implication of their experiment is that the negative glow is a region of plasma which is generated by a high speed beam of electrons emerging from the cathode dark space.

After giving up most of their energy in the negative glow, the electrons enter the Faraday dark space at very low speeds. They are then accelerated into the positive column where they again possess energy sufficient to ionize the gas.

The anode glow and dark space are believed to be manifestations of a space charge accumulation at the anode (LOEB, 1939). Also, it has been shown (DARROW, 1932) that the cathode glow is caused by collisions between neutral gas molecules and the high speed ions accelerated across the cathode fall.

Variables which can be changed to alter the characteristics of the discharge are the pressure, the gas, the interelectrode spacing, the potential and current, and the design of the cathode. If the pressure is reduced, the cathode dark space, negative glow, and Faraday dark space expand while the positive column, anode glow, and anode dark space first shrink and then disappear. Upon further reduction of the pressure, the Faraday dark space disappears, and when pressures on the order of a few microns are reached, the negative glow disappears and the cathode dark space fills the tube. At this point, the discharge is said to be obstructed, and the potential required to maintain it rises rapidly.

If the gas in the tube is changed, the spectral appearances and the lengths of the various regions of the discharge will change. This is to be expected, because the difference in ionization potentials of different gases would necessitate differences in the electron accelerating regions of the discharge.

If the interelectrode distances are changed, it will be observed that the Aston dark space, the cathode glow, the cathode dark space, the negative glow, and the Faraday dark space will move as if they are attached to the cathode. Thus, if the cathode is moved towards the anode, the positive column will diminish in length and eventually disappear while all of the aforementioned "cathode regions" will remain essentially unchanged. After the positive column has disappeared, as the cathode and anode approach one another more closely, first the Faraday dark space and then the negative glow will be displaced by the anode until once more the discharge becomes obstructed.

If the current level through a discharge is kept low enough, it will be observed that only part of the cathode will be covered with cathode glow. Thus, only part of the cathode will be participating in the discharge. Such a discharge is called a normal discharge. As the voltage is slowly increased across a normal discharge, the current will rapidly rise until the cathode is totally covered with glow. If the voltage is again increased, the current will rise more slowly, and the discharge is then said to be abnormal. In this operating range, a potential increase causes a decrease in the length of the cathode dark space and an increase in the length of the negative glow. If the potential is increased too much, increased ionic bombardment causes appreciable cathode heating, and, consequently, increased thermionic and secondary electron emission. The potential across the discharge will then decrease rapidly while current will increase rapidly. The discharge is then called an arc. The volt-ampere characteristic of a typical glow and arc discharge is given in Fig. 4.

Because the cathode is the electron emitting element of the discharge tube, the potential necessary to maintain a given discharge current will be a function of the ease with which it emits electrons. Also, because the cathode is subject to continuous positive ion bombardment, it will be eroded, and cathode material will be deposited on the tube walls. This phenomenon is known as sputtering.

CHAPTER II

THE NEGATIVE GLOW AND THE BRUSH CATHODE

The negative glow is a plasma generated by a high speed electron beam. In the normal glow, the negative glow is not long enough to be useful as a laboratory plasma. However, in a strongly abnormal glow, it is possible to have accelerating potentials across the cathode dark space capable of generating electron beams of great penetrating power.

Because ion bombardment of the cathode causes an abnormal glow with a disc cathode to degenerate into an arc very easily, a brush shaped electrode is used. The brush cathode consists of a rectangular array of pointed tungsten needles mounted onto a stainless steel base plate. Secondary and thermionic emission is minimized, because electron emission occurs at the needle points, while the ions pass by the needles and strike the base plate. High beam current levels can be maintained easily because high electric field intensities are present at the sharp needle points.

Helium was used in the present experiment because electrons penetrate through it easily (Fig. 3) and because helium has a low sputtering yield on most metals.

CHAPTER III

THE EXPERIMENTAL APPARATUS

The brush cathode used is shown in Fig. 5. It consists of about 4,000 parallel .030" diameter tungsten wires, each 1¼" long and ground to a sharp point. The needles are silver soldered into a rectangular matrix of holes drilled into a stainless steel base, 6" in diameter and 1/8" thick. Tungsten and stainless steel were chosen because of their refractory properties and their low sputtering yield with helium.

An assembly drawing of the complete discharge tube is given in Fig. 6. Note that the brush assembly fits into a matching circular depression in the ½" aluminum base plate. The base plate is sealed to the Pyrex envelope with Viton "O" rings. The Pyrex envelope is 24" in length. In order to prevent emission from the sides of the needles, the brush base, and the aluminum base plate, a Pyrex shield is fitted around the needles, and the space between the shield and the glass envelope is stuffed with glass wool. Because the greatest amount of heat dissipation in the discharge occurs at the cathode, it is necessary to provide some means for cathode cooling. The original design of the tube called for water cooling of the brush assembly, but it proved to be difficult to make the brush base leak tight. Therefore, air cooling was finally adopted and has proved to be entirely adequate.

The anode is made of stainless steel and is fitted with inlet tubes to provide lines to the vacuum pump, vacuum gauge, helium supply, and air. Also provided at the anode is an access hole through which probes can be inserted.

The entire tube assembly is mounted in a wood and Plexiglas implosion shield. A photograph of the assembly mounted on a bench is shown in Fig. 7.

The power supply used is an NJE Model H5-200 which is capable of delivering up to 5 kv at 250 ma. Nine extra 5 mf capacitors are paralleled onto the output for extra smoothing. This was necessary because the peak to peak ripple on the output is about 10% of the DC level. In order to eliminate any instabilities in discharge operation due to negative resistance characteristics, a 10,000 ohm stabilizing resistor is used in series with the supply.

A Welch Duo-Seal #1402B one-half hp vacuum pump is used, and vacua between 1 and 2 microns are attainable in the tube. As in most vacuum devices, leaks were a source of difficulty in the early stages of experimentation, but they were eliminated after some detective work. One particularly evasive source of leaks was the rubber hose used for interconnection of the components. Several samples of hose were tried, but all permitted very slow seepage of air into the system, the seepage rate being proportional to the hose length. This seepage problem was alleviated by using copper for all long interconnecting lines and using the rubber hose for short couplings only.

CHAPTER IV

OPERATION OF THE BRUSH CATHODE DISCHARGE

The volt ampere characteristics of the tube are given in Figs. 8 through 15 for pressures between 100 and 1200 μ. The following description of the discharge refers to the observation done at 1200 μ.

Breakdown occurs at about 400 v. Between 4 and 10 ma, the discharge appears as in Fig. 16. The cathode glow forms a thin layer over the brush points, and extends into the brush itself, so that the wires appear surrounded with a pink glow. Above the cathode glow we find the cathode dark space which, in turn, is separated from the negative glow by a sharp border. The negative glow gives way to the Faraday dark space and then the positive column. As the current is increased, the cathode dark space contracts slightly, the negative glow expands, and the positive column shrinks, as in Fig. 17. When the current is increased sufficiently, the negative glow extends all the way to the anode and is very uniform in appearance. This point is shown on the volt ampere characteristics of the discharge.

At lower pressures, the negative glow reaches the anode at successively lower currents, so that, at 100 and 200 μ, the negative glow reaches the anode over the whole operating range.

Similar descriptions apply to Figs. 8 through 14, except that in Figs. 8 and 9, the negative glow reaches the anode over the whole operating range.

CHAPTER V

LANGMUIR PROBE STUDIES

Since the nineteenth century, the sounding electrode, or probe, has been used as a tool for studying the properties of the gaseous discharge. Hittorf (1883), Skinner (1899), and other early researchers tried to determine the potential distribution in the discharge by measuring the potential acquired by insulated probes situated along the length of the discharge. They understood that the presence within the discharge of oppositely charged particles of different masses and velocities could cause the probe and plasma potentials to differ. For example, a probe immersed in a neutral sea of high speed electrons and low speed positive ions would assume a potential sufficiently negative to enable the ions and electrons to strike it in equal numbers. Unfortunately, the work of the early researchers suffered great limitations because they did not know how to determine the magnitude of the difference between the probe and plasma potentials.

It remained for Langmuir (1923 and 1924) to develop the theory of the probe so that reasonable estimates of densities, temperatures, and potentials could be obtained through its use. Langmuir considered the probe to anode volt-ampere characteristics. In the present experiment, the probe was used to measure electron temperature and density.

To understand how the volt-ampere characteristics of the probe can lead us to a knowledge of electron temperature and density, let us consider a strongly negative probe immersed in a plasma of positive ions and electrons with a Maxwellian energy distribution. Under this condition, the probe will atract the ions and repel the electrons. Now if the probe is made more positive, a point will be reached at which the kinetic energy of some electrons will be sufficient to enable them to reach the probe. This region starts at point A on the typical probe curve in Fig. 18. As the probe is made more positive, more and more electrons will reach the surface, until, when the potential of the probe reaches that of the surrounding space, the probe receives all of the ions and electrons which would pass through a correpsonding area outside of the probe vicinity. This is point B in Fig. 18. Above the space potential, as the probe is made more positive, a negative space charge sheath is formed around the probe and the current rises only slowly.

Electron energy distributions other than Maxwellian will result in different probe curves. If, for example, a high energy beam of electrons is present, the electrons will reach the probe once its potential is insufficient to repel them. The probe curve will then exhibit a sharp current rise within a very small voltage range.

It should be noted that if no electrons were present, the curve would follow the extrapolated line AC. The ion component of the current, therefore, is given by this line. This ion component is subtracted from the total current to find the electron contribution.

We begin a quantitative analysis of the region AB of Fig. 18 by assuming that the electrons have a Maxwellian energy distribution. Boltzmann's relation then predicts that

$$N_{EP} = N_{ED} \exp\left(\frac{-eV}{kT_E}\right)$$

where

V is the potential of the probe relative to the plasma

T_E is the electron temperature

N_{EP} is the electron density at the probe surface

N_{ED} is the electron density in the discharge plasma

k is Boltzmann's constant

e is the charge of an electron

Similarly, if J_{EP} is the electron current density to the probe and J_{ED} is the random plasma electron current density, then

$$J_{EP} = J_{ED} \exp\left(\frac{-eV}{kT_E}\right)$$

and $$\ell n\ J_{EP} = \ell n\ J_{ED}\ \frac{-eV}{kT_E}$$

Thus, if the logarithm of J_{ED} is plotted vs. V, then T_E can be found from the slope of this line, $\frac{e}{kT_E}$.

At point B of Fig. 18, this linear relation breaks down. Here, the probe is at the plasma potential, and the probe receives all of the ions and electrons which would pass through a corresponding area outside the vicinity of the probe. From kinetic theory, we know that

$$J_{ED} = \frac{N_{ED}\ e\ U_{ED}}{4}$$

where

J_{ED} is the random electron current density

U_{ED} is the average thermal velocity of the electrons

e is the electron charge

N_{ED} is the electron density

At point B, now,

$$J_{ED} = J_{EP} = \frac{N_{ED}\ e\ U_{ED}}{4}$$

and $$U_{ED} = \sqrt{\frac{8kT_E}{\pi m_e}}$$

where m_e is the electron mass.

so $$J_{ED} = J_{EP} = eN_{ED}\sqrt{\frac{kT_E}{2\pi m_e}}$$

If T_E is known from the slope of the line AB, then N_{ED} can be found, for

$$N_{ED} = \frac{J_{ED}}{e}\sqrt{\frac{2\pi m_e}{kT_E}}$$

CHAPTER VI

USE OF THE LANGMUIR PROBE WITH THE BRUSH CATHODE DISCHARGE

The probe design used in this experiment is illustrated in Fig. 19. The probe is mounted axially in the tube in order to minimize any effects of the tube walls on the probe characteristics. Volt-ampere characteristics of the probe were obtained by sweeping the voltage on the probe very slowly with a motor driven precision potentiometer. The current was monitored by an electrometer whose output was fed to one channel of a dual channel chart recorder. Voltage was monitored by a digital voltmeter which fed pulses at 1/10 v sweep increments into the second channel of the chart recorder. A block diagram of this data recording system is given in Fig. 20.

From the beginning, considerable difficulty was encountered in obtaining reproducible probe characteristics. Other workers (PERSSON, 1965 and KOSTELNICEK, 1965) have encountered similar difficulties, and they have attributed them to the formation of a layer of impurities on the probe. Because such a layer would give rise to a change in the probe contact potential, any variation in the layer would cause a variation in the probe characteristics. The layer could consist of an oxide film, condensed vacuum oil, or any other foreign substance present in the system. The use of a cold trap and diffusion pump in the vacuum system would undoubtedly reduce the contaminant level. These accessories were unavailable for the present experiment, however, so the contaminants remained in the system.

The film of contaminants was removed from the probe and anode periodically be reversing the discharge current and by running the probe as an auxiliary cathode, thereby bombarding the probe and anode with positive ions. Unfortunately, this cleaning effect did not last more than about 10 sec at discharge currents of about 1 ma, and only about 1 sec at higher currents. Therefore, it was necessary to "clean" the probe every 10 sec during a sweep in order to obtain reproducible probe curves even at the low current levels. The cleaning was done automatically by a timing device which connected the probe, via a 10 meg resistor, to the cathode for a duraction of ½ sec at intervals of 10 sec. The schematic of this device is given in Fig. 21. Even with the cleaner, however, it was impossible to obtain reproducible curves at high current levels.

CHAPTER VII

RESULTS OF THE PROBE STUDIES

The probe characteristics finally obtained are given in Figs. 22 through 25 for discharge currents and pressures of (1 ma, 100μ), (2 ma, 200μ), (2 ma, 300μ), (2 ma, 400μ) respectively. Characteristics for higher currents were unobtainable for the reasons outlined in the previous section. The electron temperatures and densities calculated from the probe characteristics are tabulated below.

DISCHARGE CURRENT	PRESSURE	T_E	N_{ED}
2 ma	400 μ	735°K	1.46×10^8 cm^{-3}
2 ma	300 μ	760°K	2.74×10^8 cm^{-3}
2 ma	200 μ	660°K	1.89×10^8 cm^{-3}
1 ma	100 μ	633°K	5.67×10^7 cm^{-3}

CHAPTER VIII

CONCLUSION

The brush cathode discharge tube constructed for the present experiment is capable of producing a very stable abnormal glow discharge. The negative glow of this discharge is quite uniform, and it can be made to extend all the way to the anode. These properties make the negative glow useful as a laboratory plasma.

The probe measurements of the negative glow were made only at low pressures and discharge currents. They show that the electron temperature is quite low (approximately $700^{o}K$) and that the electron density is approximately 10^{8} per cc. Higher pressures and currents would show higher electron densities.

Because the probe measurements were hampered by the presence of foreign substances within the system which formed contaminating layers on the probe and anode surfaces, it is suggested that, in the future, a diffusion pump be used to evacuate the system, and a cold trap be used between the pump and the tube. These steps should reduce the level of contaminants significantly and should, therefore, greatly facilitate probe measurements.

Consideration might also be given to the future use of faster sweep frequencies so that probe curves could be determined in seconds. Van Berkel (1938) has found the probe characteristics to be dependent upon sweep frequency. However, the dependency he noted could be due to the fact that the probe is bombarded by ions during the negative part of the sweep. Thus, at high sweep frequencies, the probe will be cleaned by ionic bombardment for shorter period of time than at low frequencies, while the intervals between cleanings will be longer at low frequencies. Therefore, if the system could be made sufficiently free of contaminants so that the probe would remain clean for a long time, the probe characteristics should be independent of sweep frequency.

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W. P. J. Van Berkel, "Einflusz von Anderungen des Sondenzustandes auf Sondencharakteristiken nach Langmuir," Physica 5, 230 (1938).

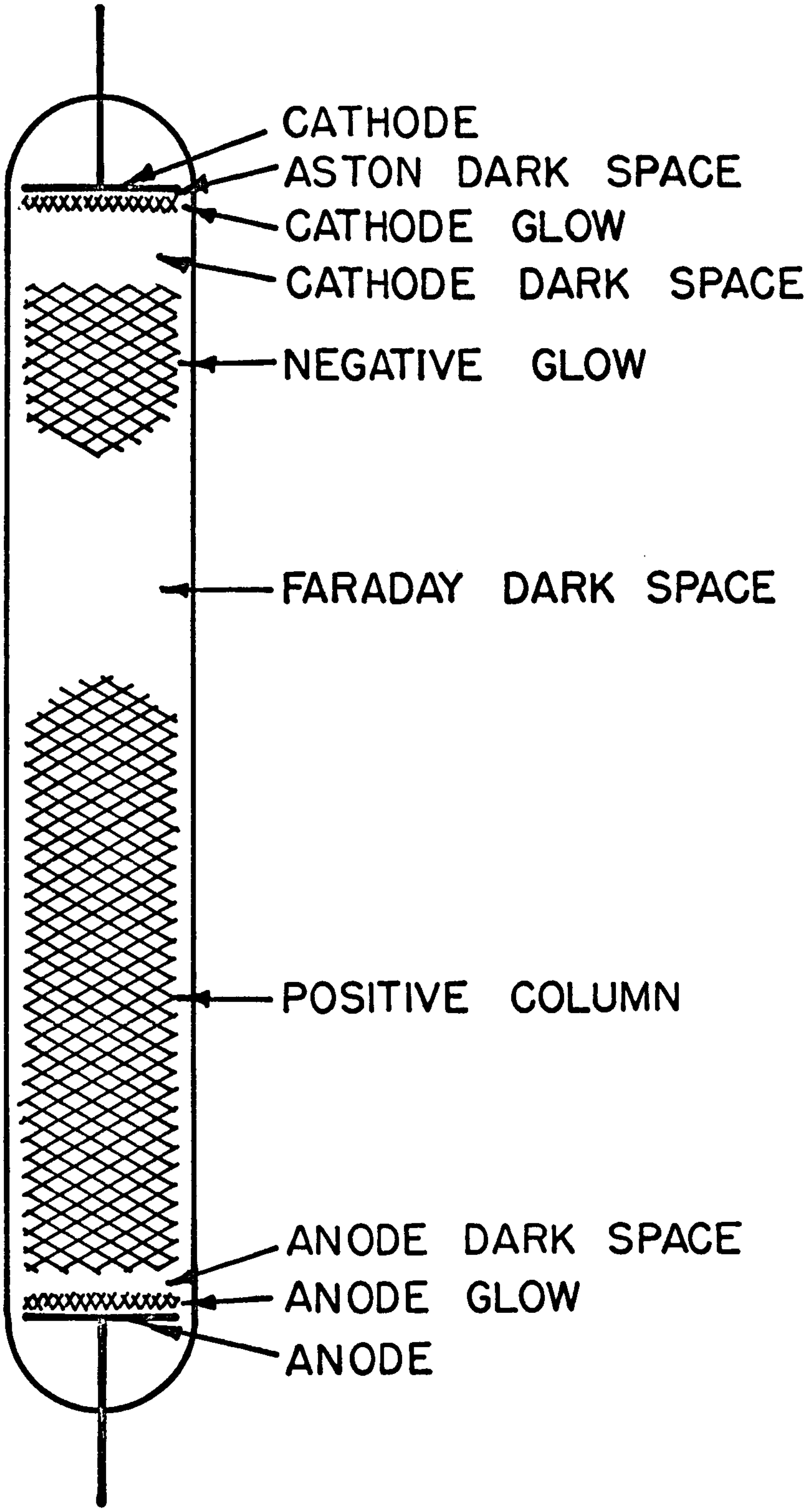

CATHODE
ASTON DARK SPACE
CATHODE GLOW
CATHODE DARK SPACE
NEGATIVE GLOW
FARADAY DARK SPACE
POSITIVE COLUMN
ANODE DARK SPACE
ANODE GLOW
ANODE

Fig. 1

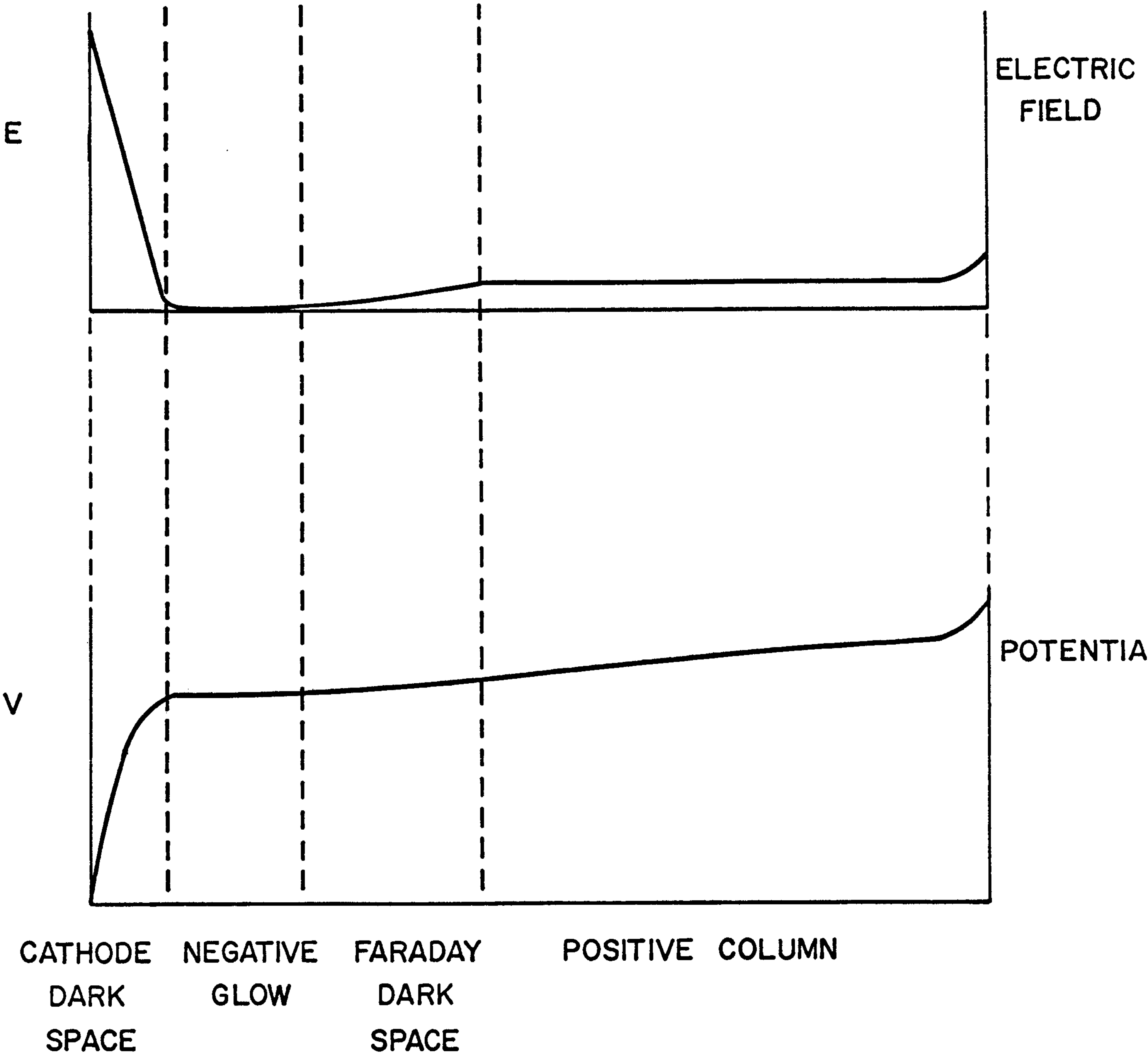

E
ELECTRIC FIELD
V
POTENTIA
CATHODE DARK SPACE
NEGATIVE GLOW
FARADAY DARK SPACE
POSITIVE COLUMN

Fig. 2

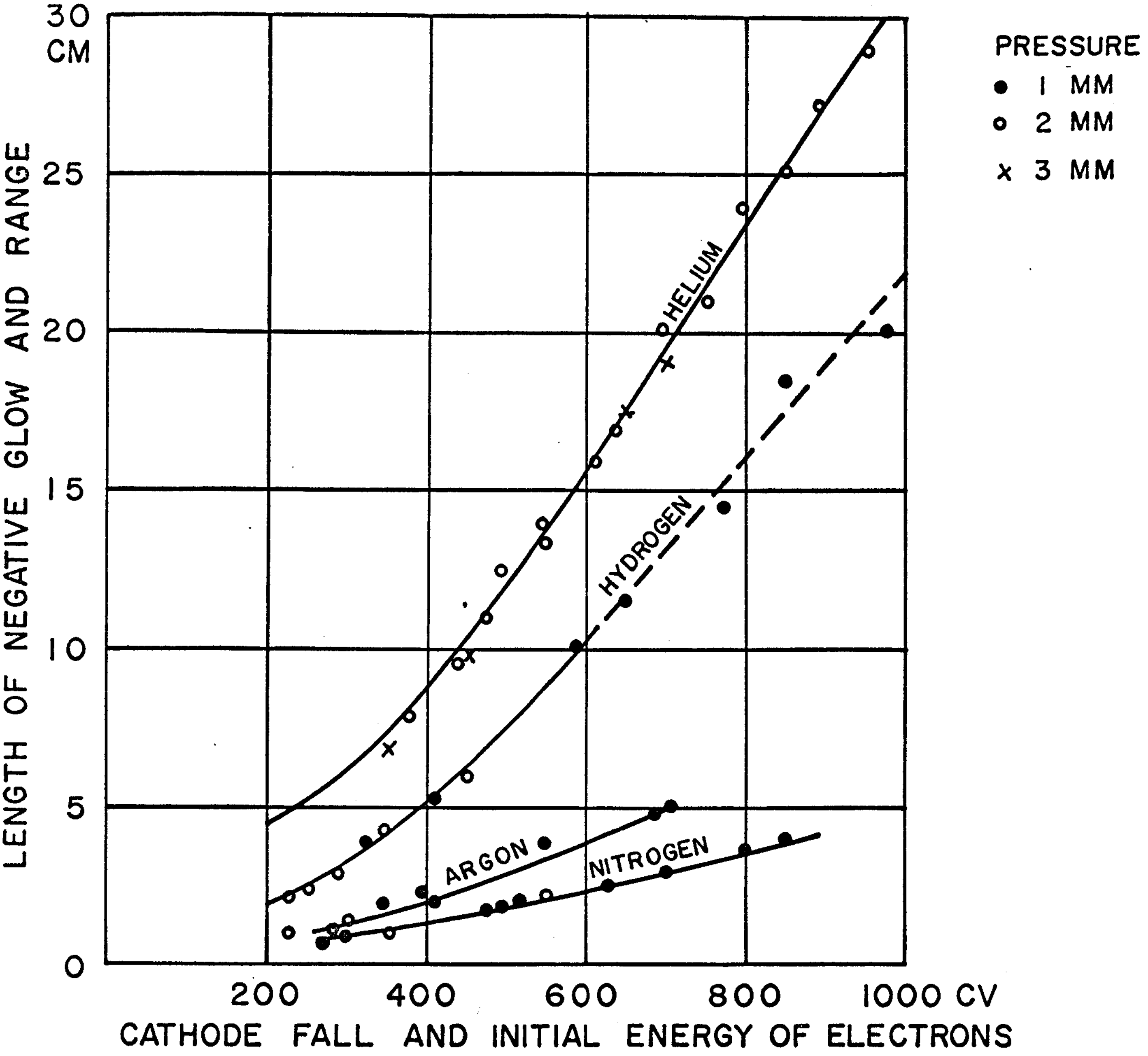

30 CM
25
20
15
10
5
0
LENGTH OF NEGATIVE GLOW AND RANGE
200
400
600
800
1000 CV
CATHODE FALL AND INITIAL ENERGY OF ELECTRONS
HELIUM
HYDROGEN
ARGON
NITROGEN
PRESSURE
● 1 MM
○ 2 MM
× 3 MM

Fig. 3

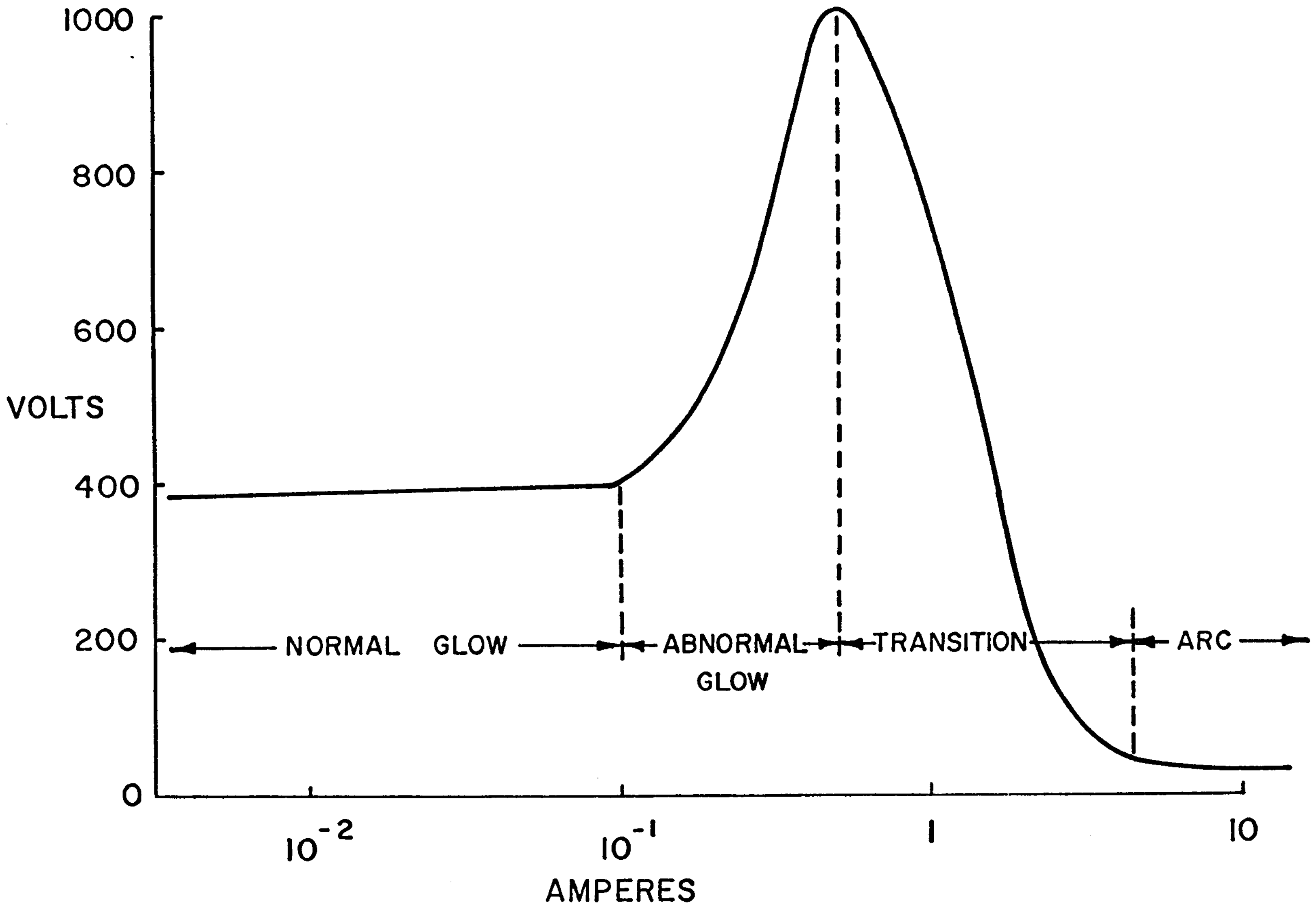

1000
800
600
VOLTS
400
200
0
NORMAL GLOW
ABNORMAL GLOW
TRANSITION
ARC
10^{-2}
10^{-1}
1
10
AMPERES

Fig. 4

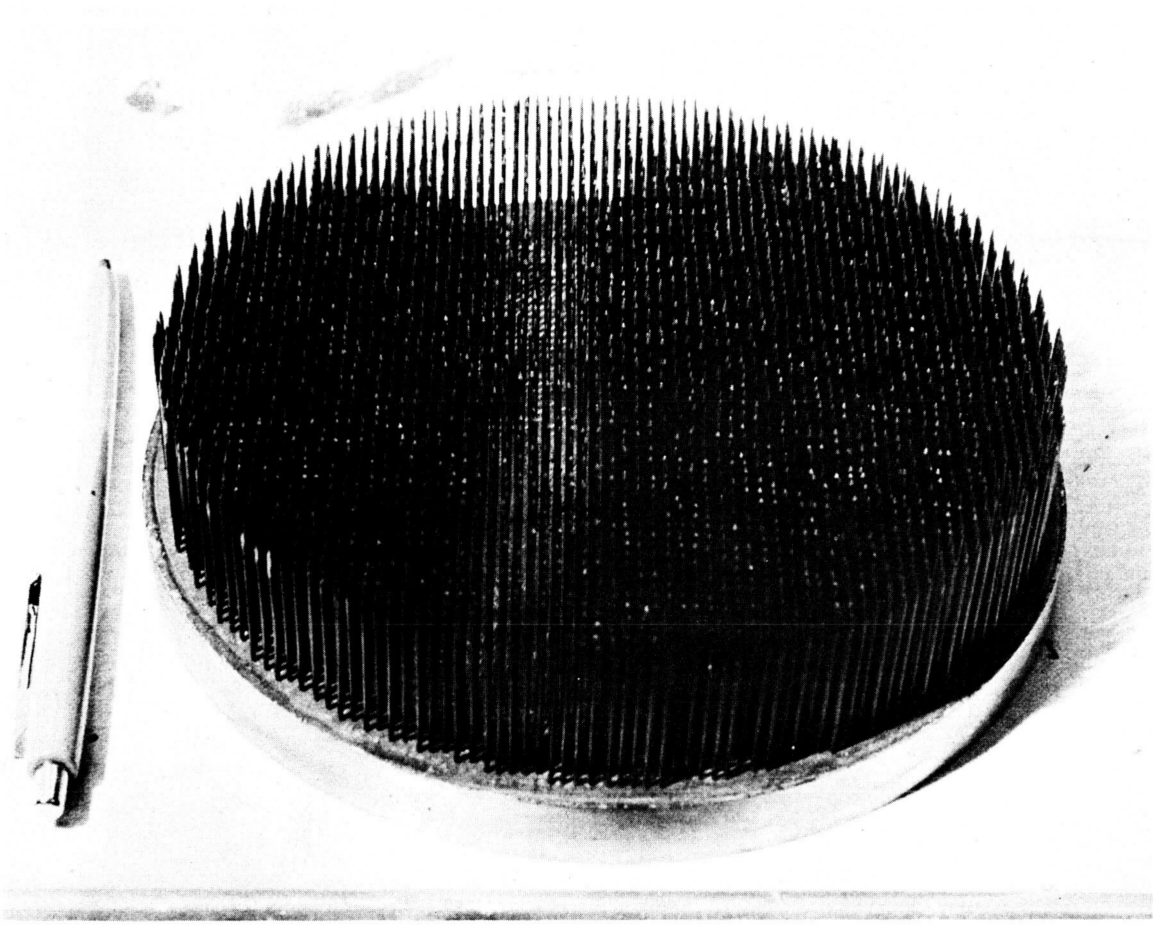


FIG. 5 PHOTOGRAPH OF THE BRUSH CATHODE

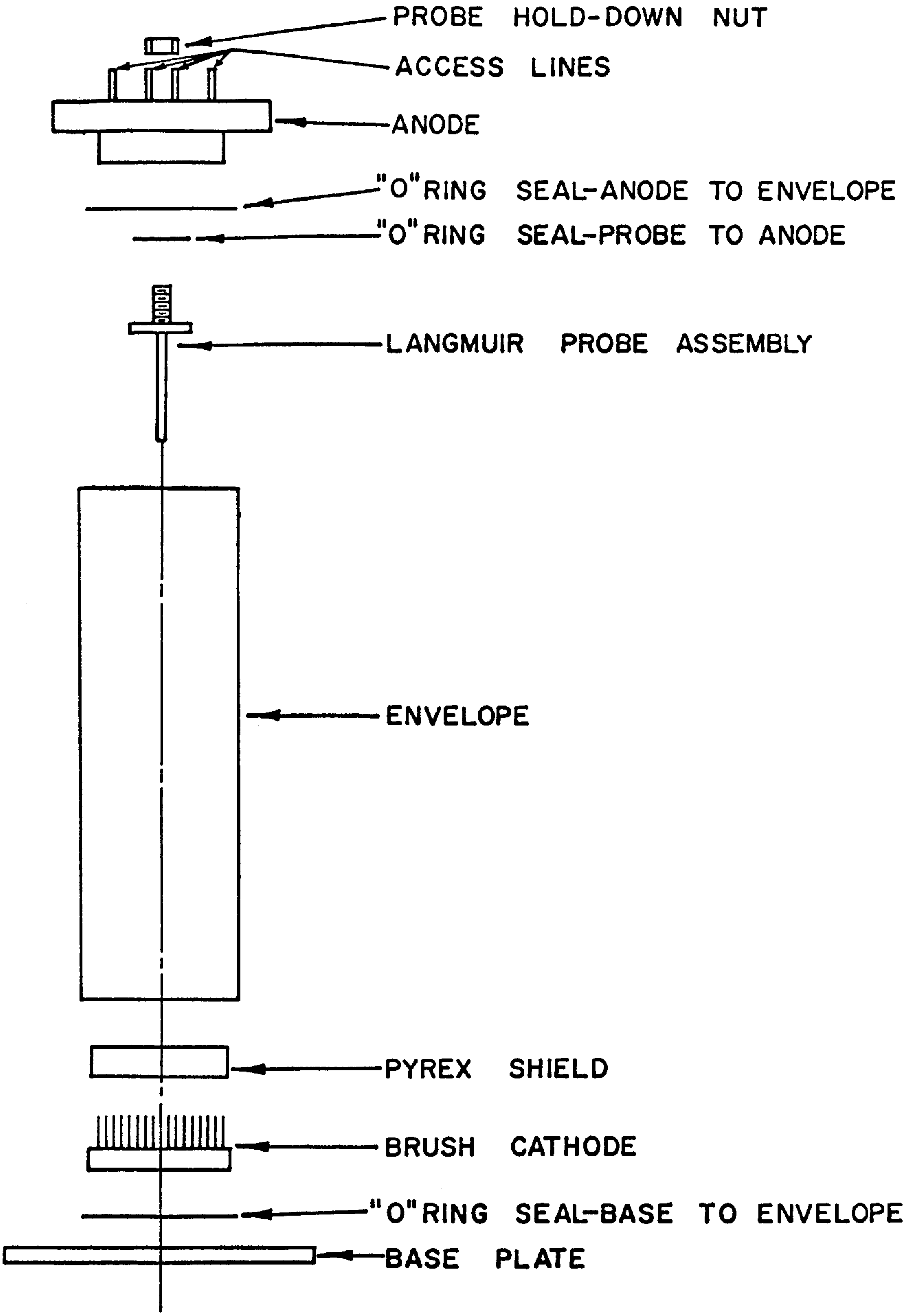

PROBE HOLD-DOWN NUT
ACCESS LINES
ANODE
"O" RING SEAL-ANODE TO ENVELOPE
"O" RING SEAL-PROBE TO ANODE
LANGMUIR PROBE ASSEMBLY
ENVELOPE
PYREX SHIELD
BRUSH CATHODE
"O" RING SEAL-BASE TO ENVELOPE
BASE PLATE

Fig. 6

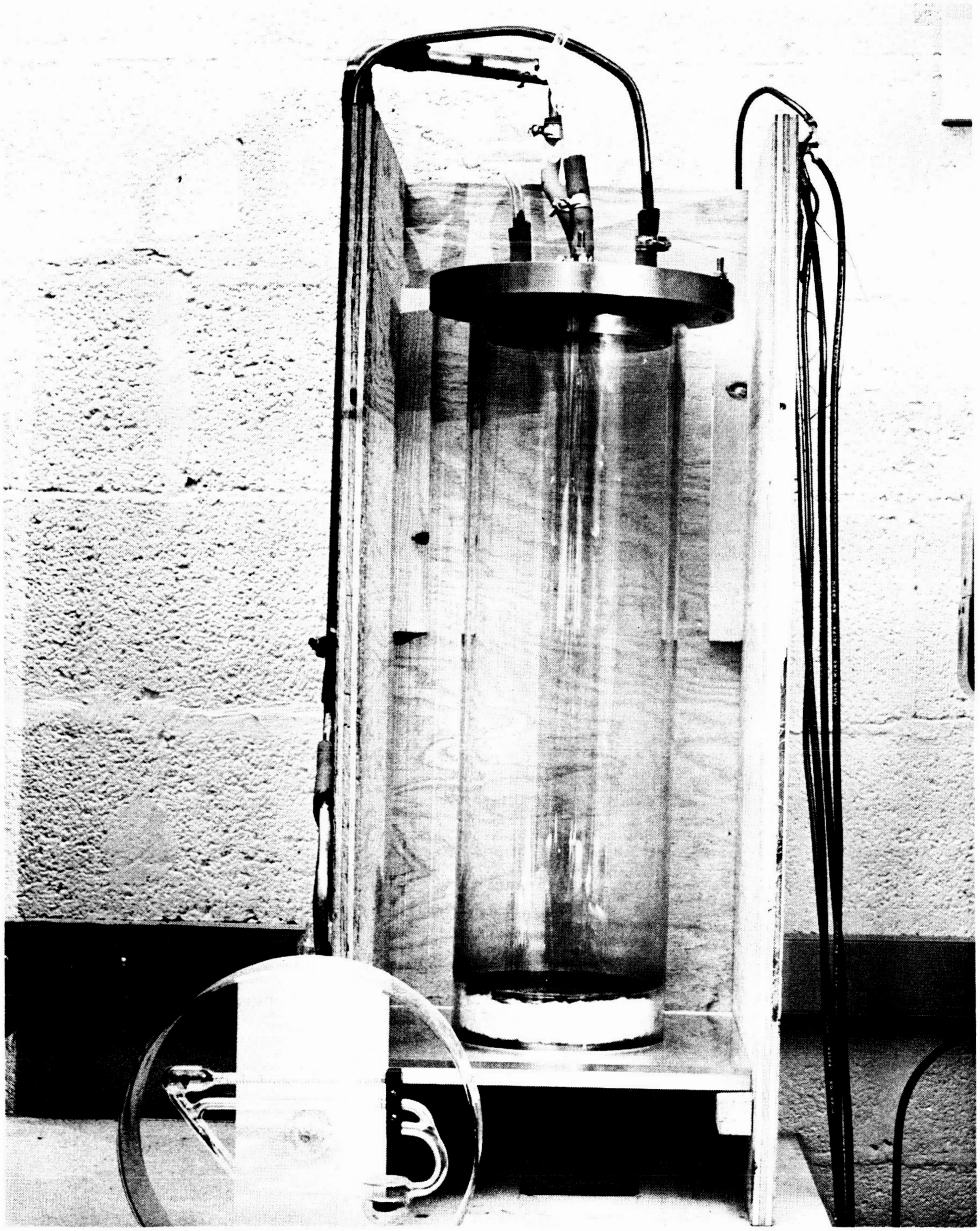


FIG. 7 PHOTOGRAPH OF THE TUBE ASSEMBLY MOUNTED ON A LABORATORY BENCH

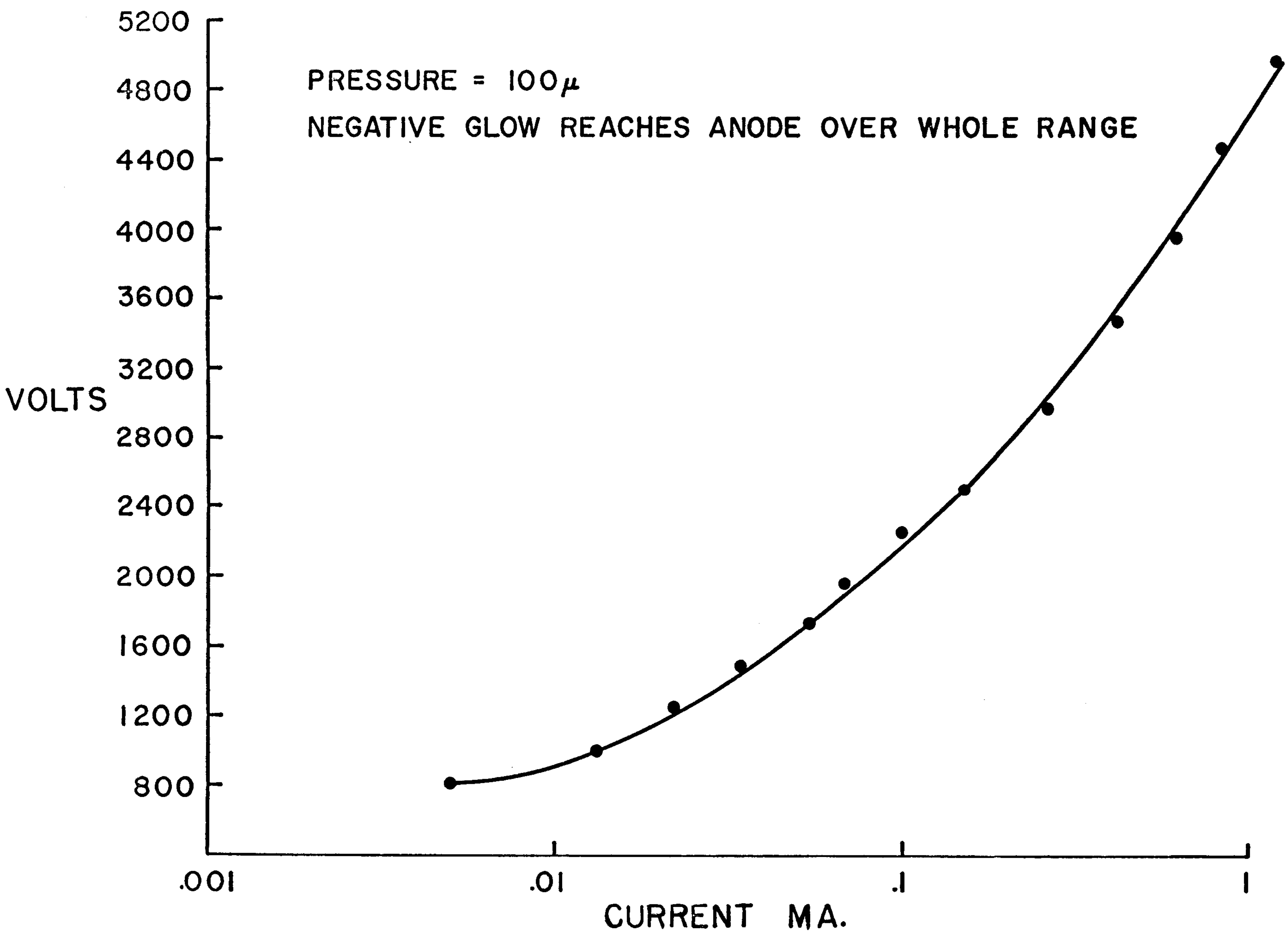
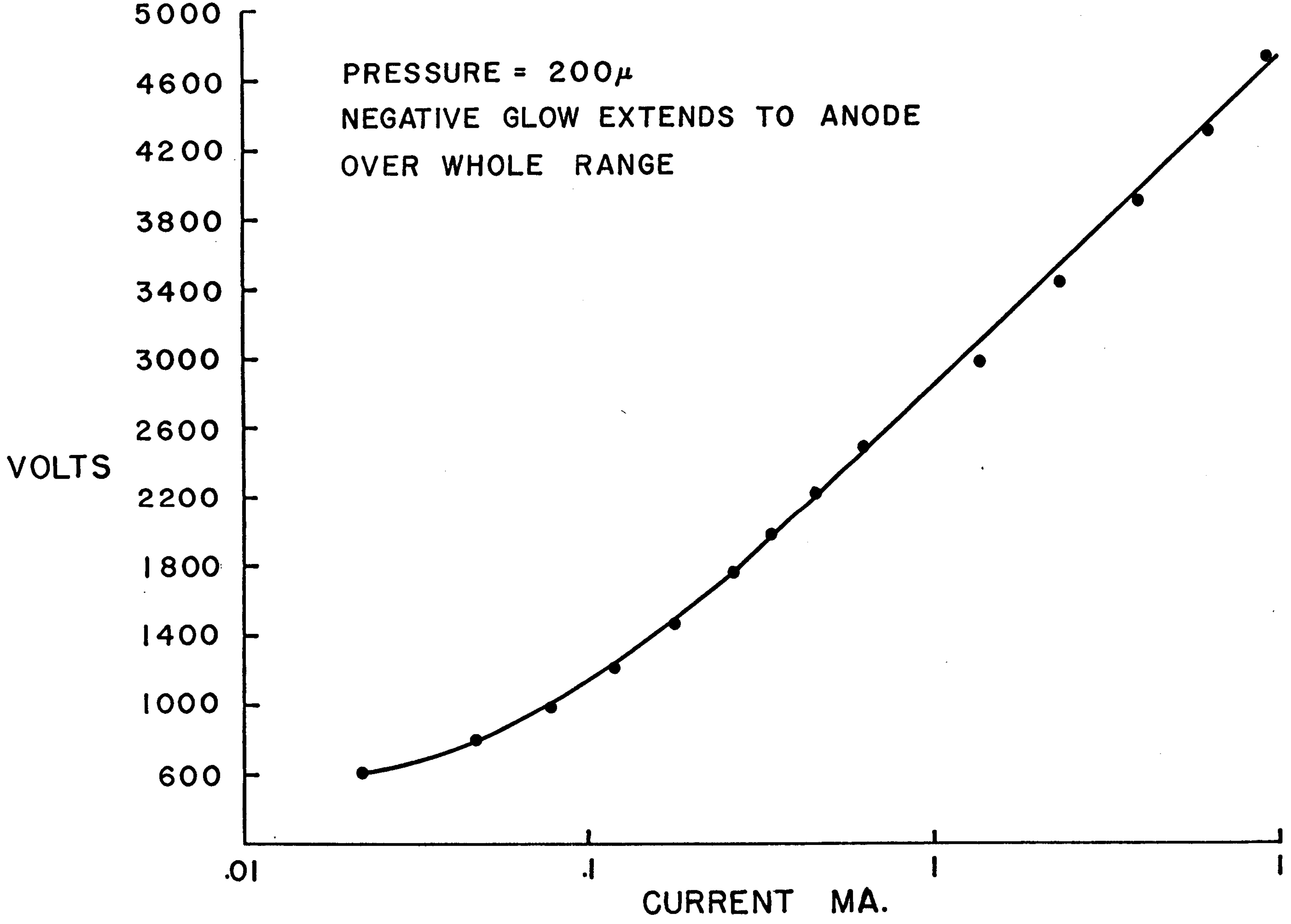

PRESSURE = 100μ
NEGATIVE GLOW REACHES ANODE OVER WHOLE RANGE
VOLTS
5200
4800
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
.001
.01
.1
1
CURRENT MA.

Fig. 8


PRESSURE = 200μ
NEGATIVE GLOW EXTENDS TO ANODE
OVER WHOLE RANGE
VOLTS
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4600
4200
3800
3400
3000
2600
2200
1800
1400
1000
600
.01
.1
1
1
CURRENT MA.

Fig. 9

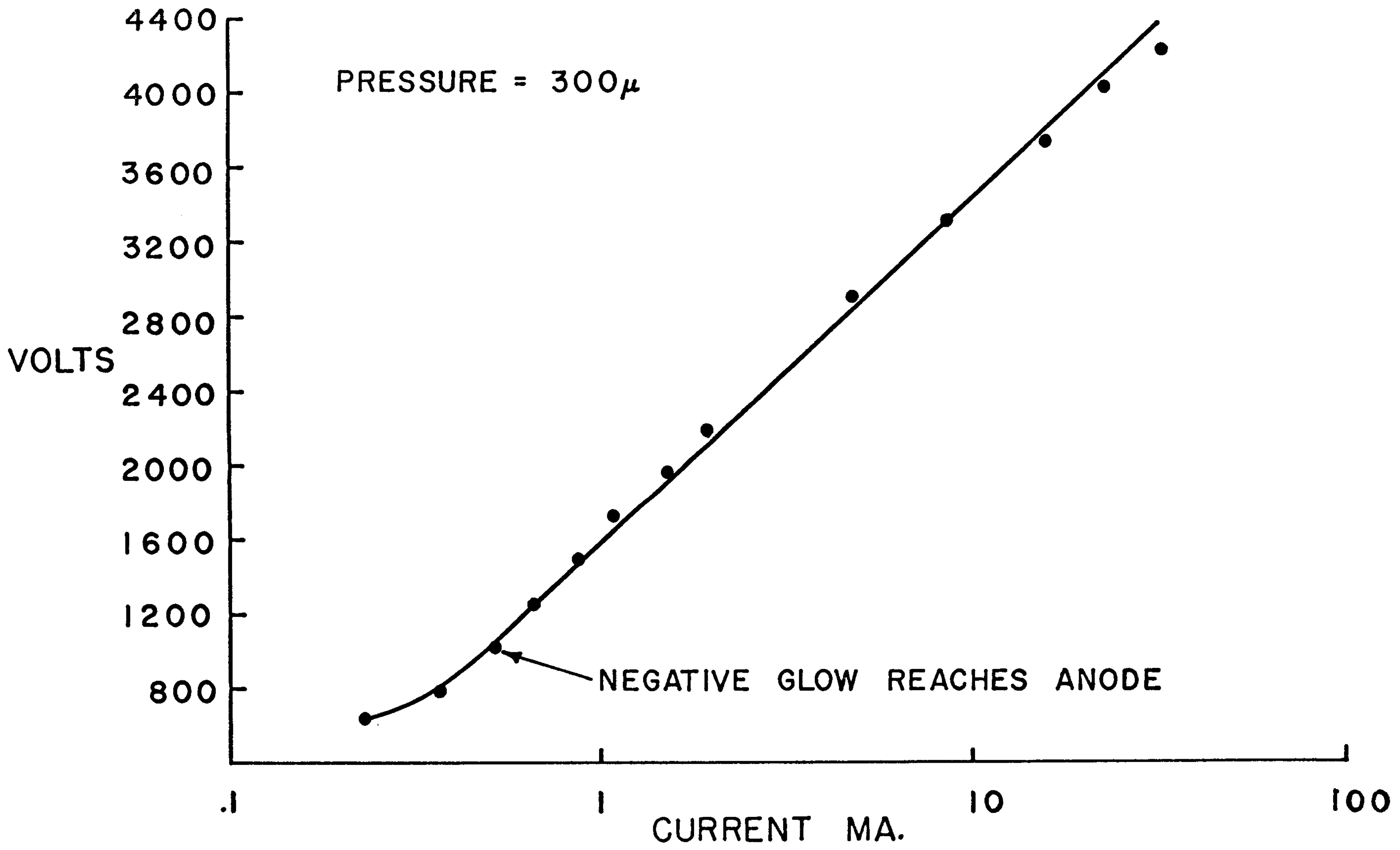

4400
4000
3600
3200
2800
VOLTS
2400
2000
1600
1200
800
PRESSURE = 300μ
NEGATIVE GLOW REACHES ANODE
.1
1
10
100
CURRENT MA.

Fig. 10

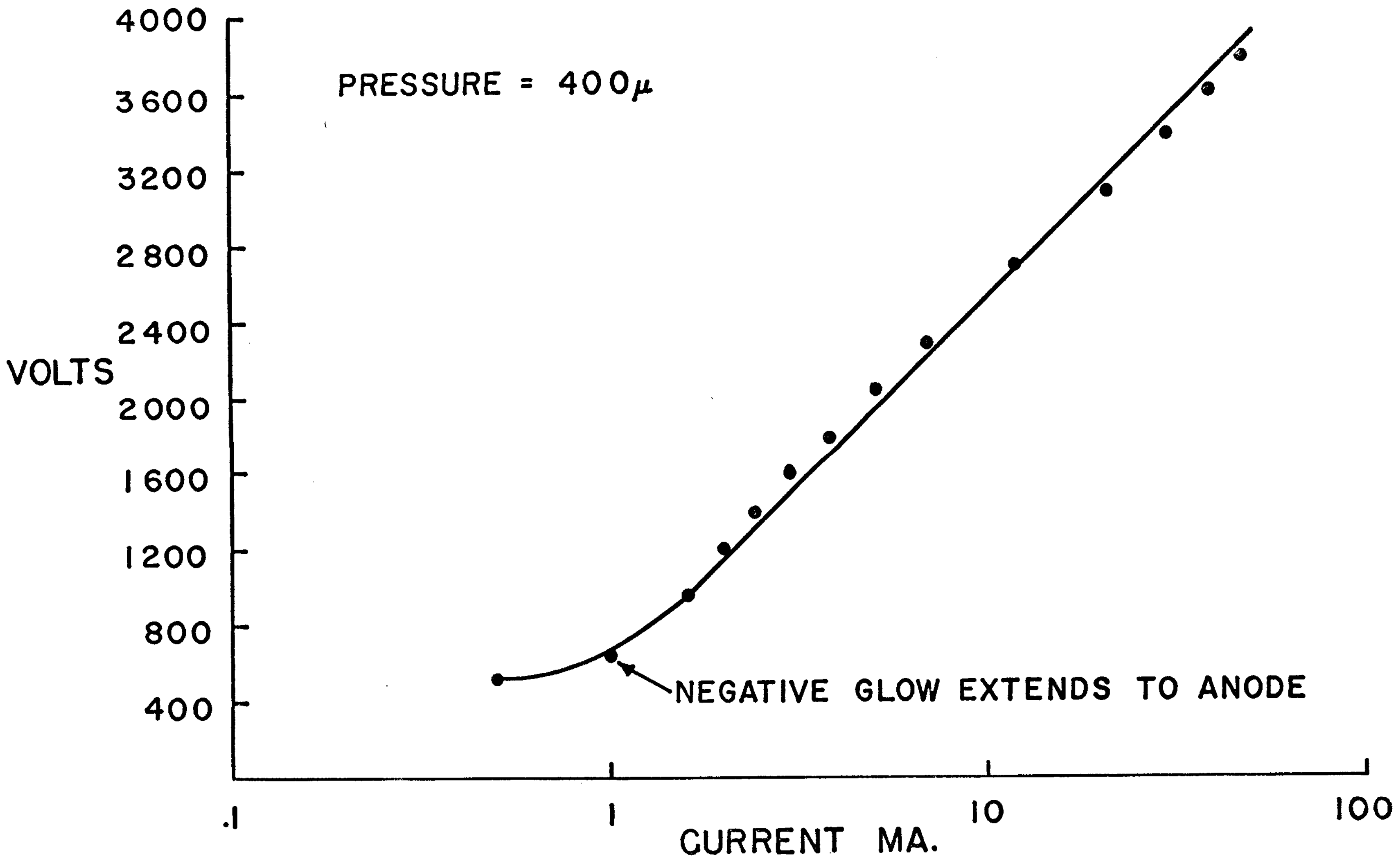

PRESSURE = 400μ
VOLTS
4000
3600
3200
2800
2400
2000
1600
1200
800
400
NEGATIVE GLOW EXTENDS TO ANODE
.1
1
10
100
CURRENT MA.

Fig. 11

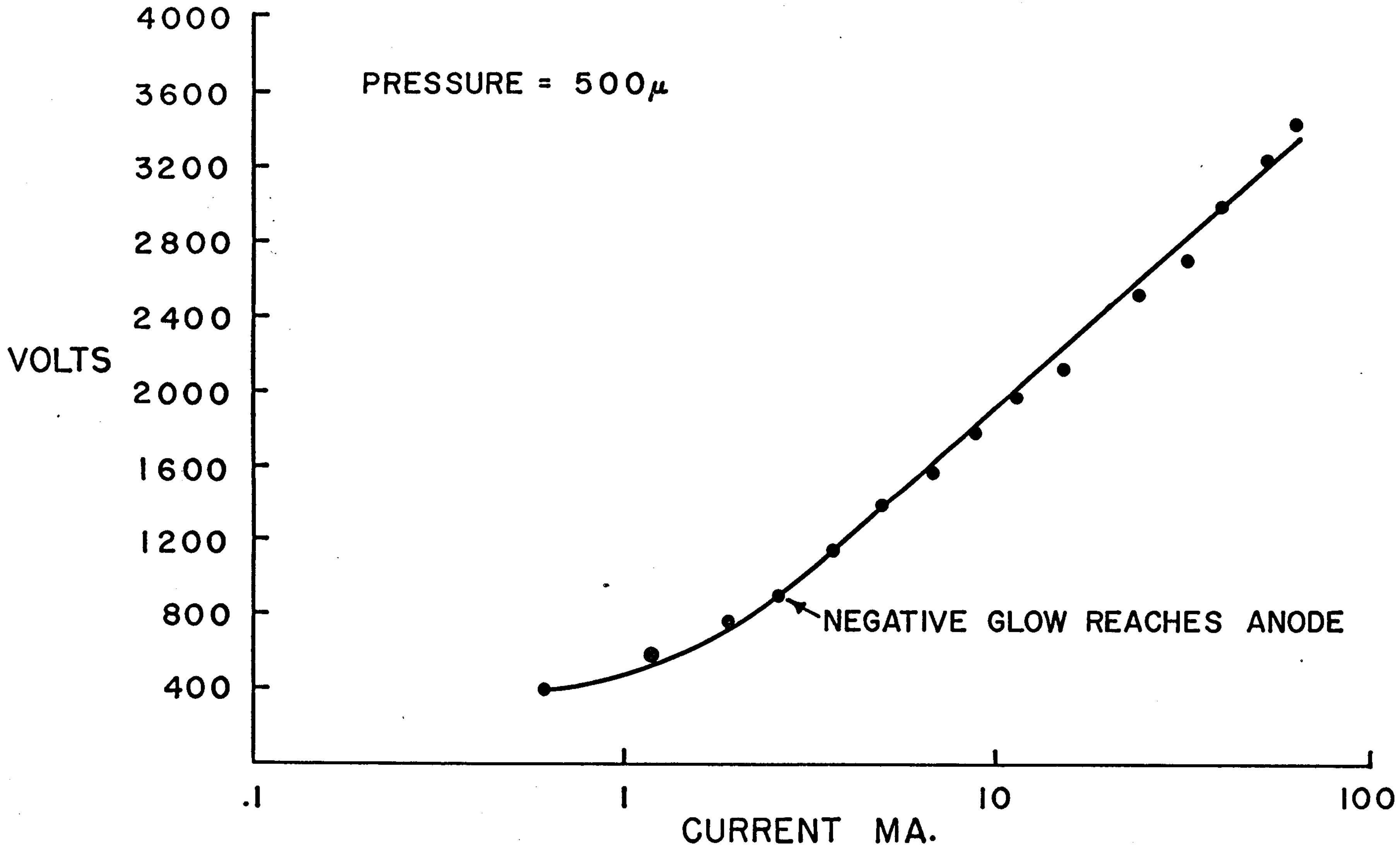

4000
3600
3200
2800
2400
2000
1600
1200
800
400
VOLTS
PRESSURE = 500μ
NEGATIVE GLOW REACHES ANODE
.1
1
10
100
CURRENT MA.

Fig. 12

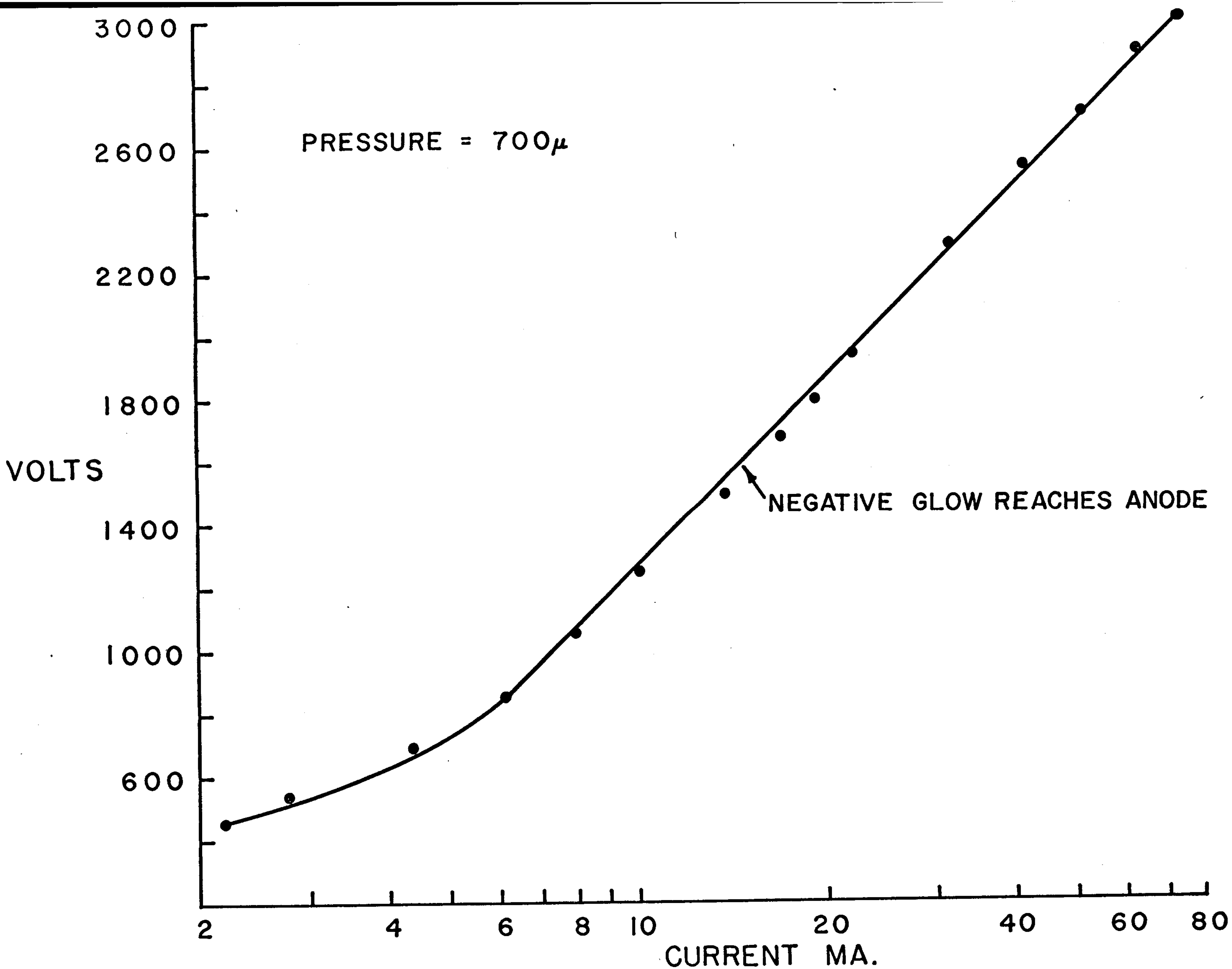

3000
2600
2200
1800
1400
1000
600
VOLTS
PRESSURE = 700μ
NEGATIVE GLOW REACHES ANODE
2
4
6
8
10
20
40
60
80
CURRENT MA.

Fig. 13

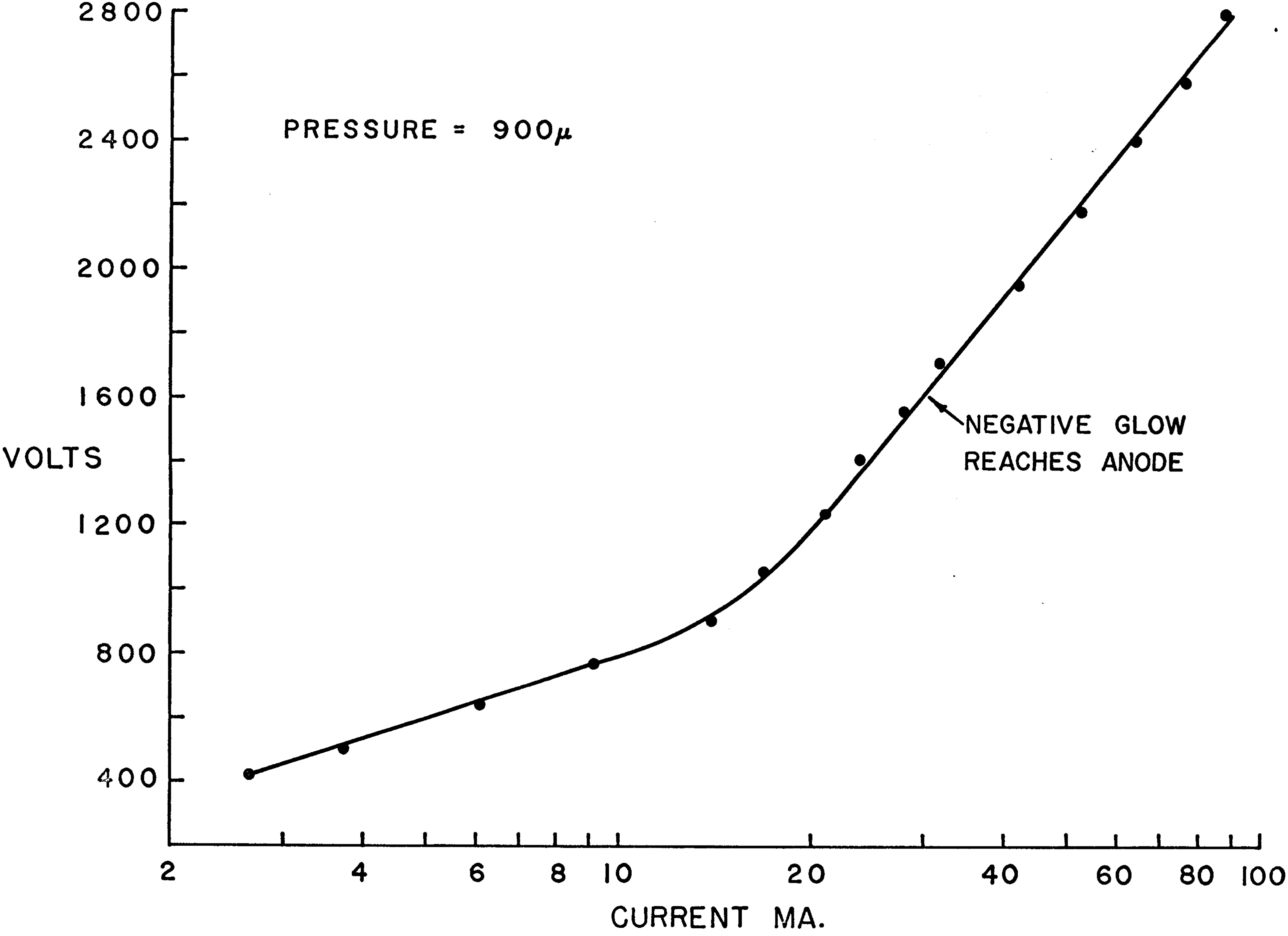

2800
2400
2000
1600
1200
800
400
VOLTS
PRESSURE = 900μ
NEGATIVE GLOW
REACHES ANODE
2
4
6
8
10
20
40
60
80
100
CURRENT MA.

Fig. 14

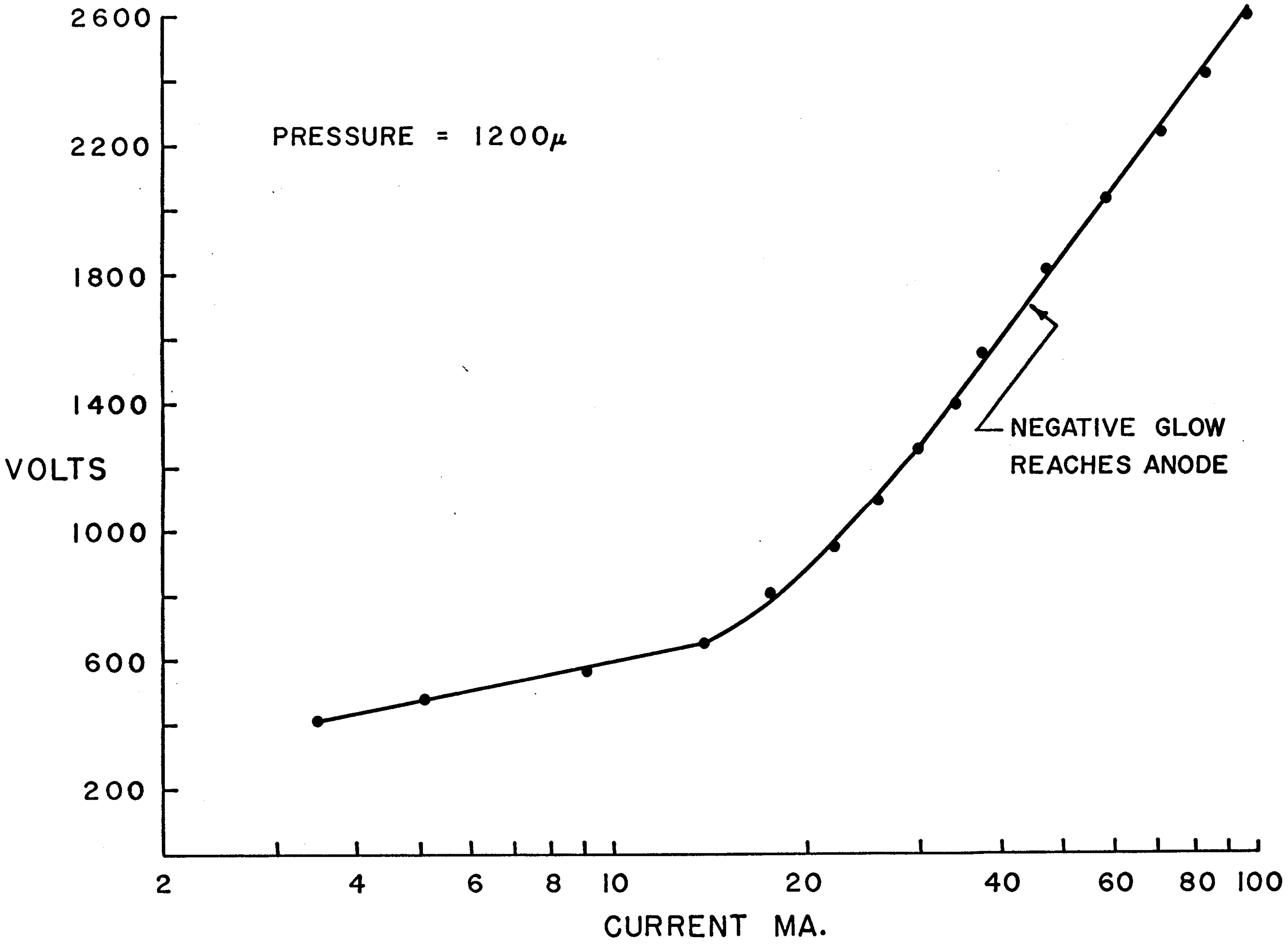

PRESSURE = 1200μ
VOLTS
2600
2200
1800
1400
1000
600
200
CURRENT MA.
2
4
6
8
10
20
40
60
80
100
NEGATIVE GLOW REACHES ANODE

Fig. 15

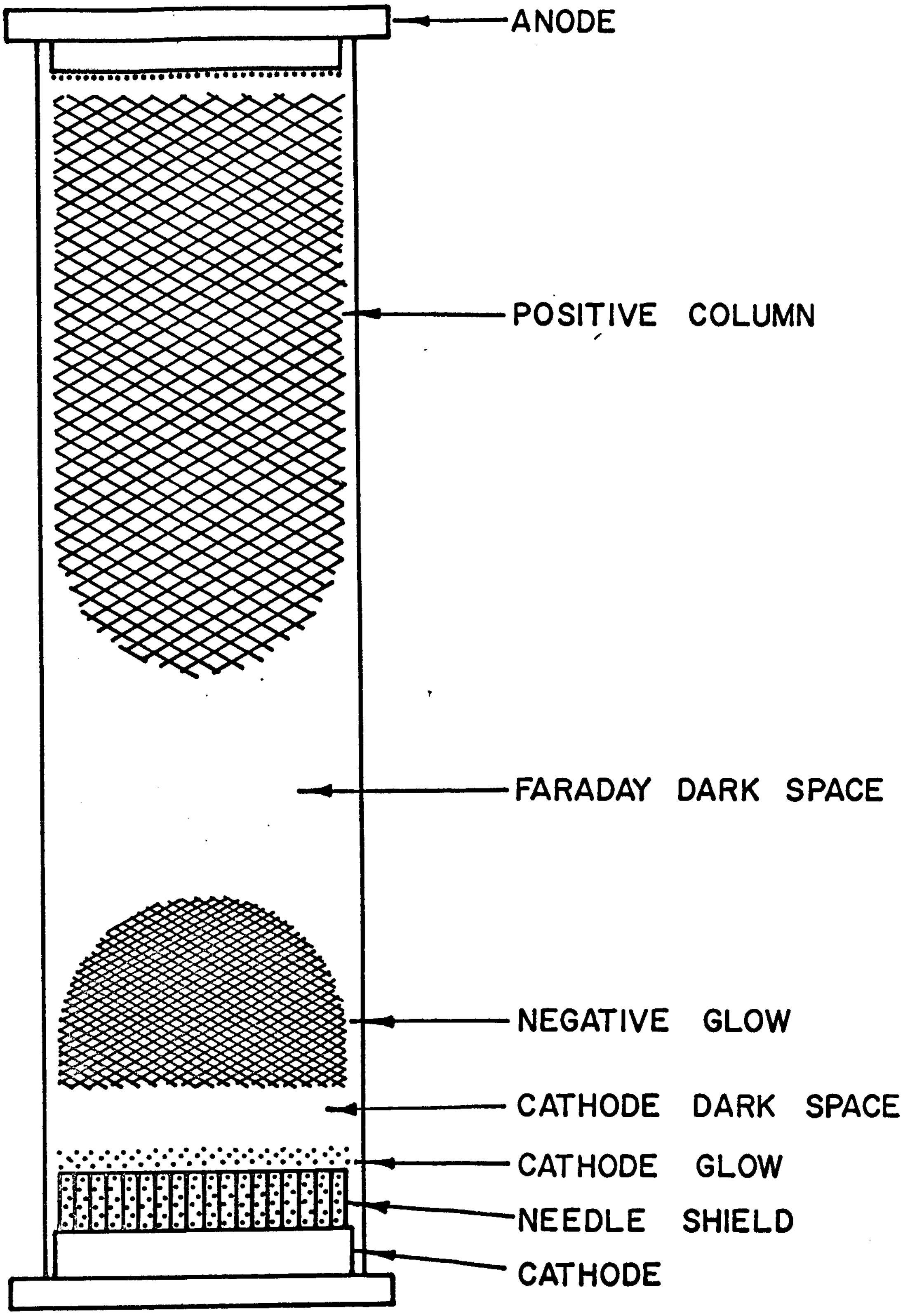

ANODE
POSITIVE COLUMN
FARADAY DARK SPACE
NEGATIVE GLOW
CATHODE DARK SPACE
CATHODE GLOW
NEEDLE SHIELD
CATHODE

Fig. 16

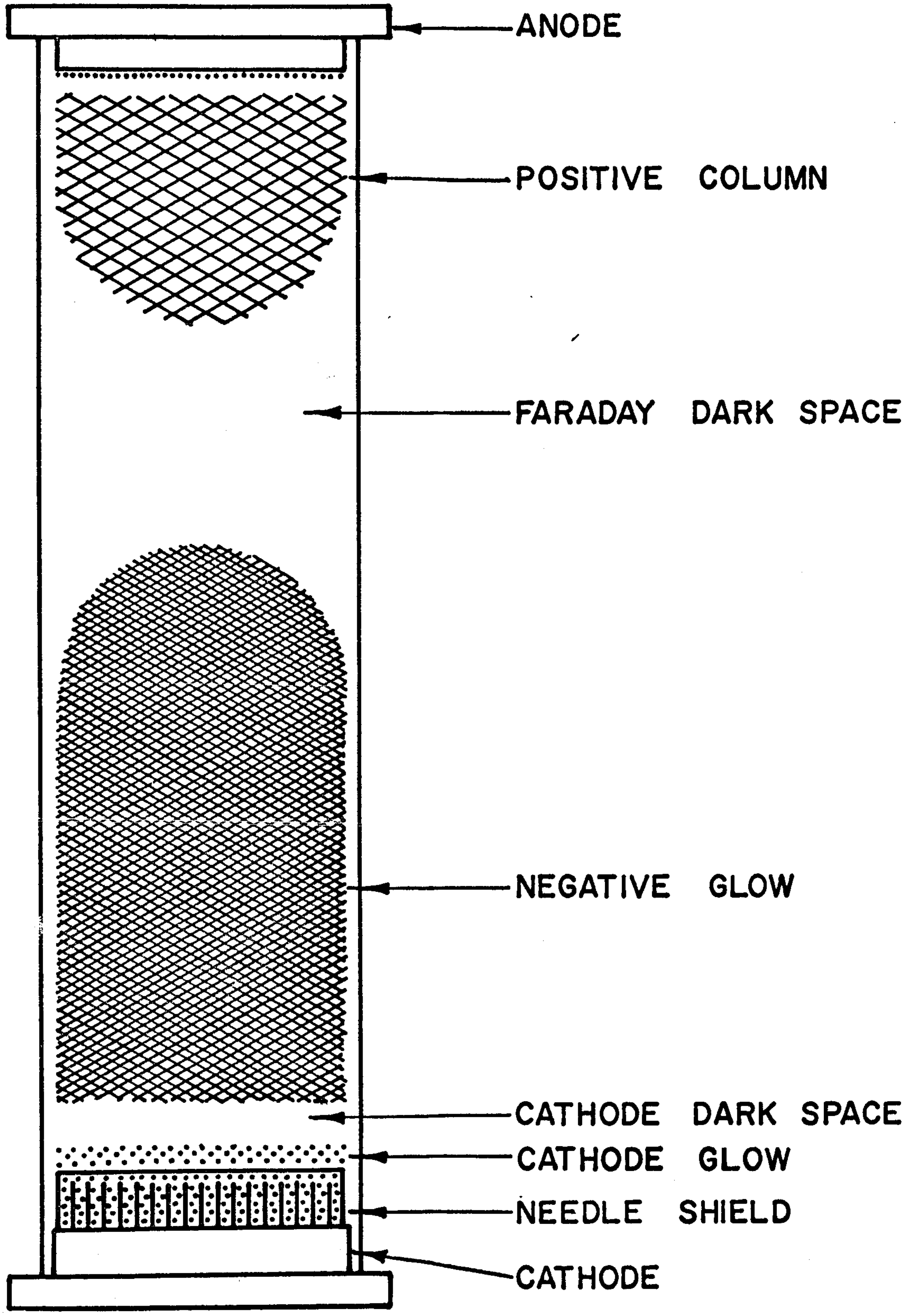

ANODE
POSITIVE COLUMN
FARADAY DARK SPACE
NEGATIVE GLOW
CATHODE DARK SPACE
CATHODE GLOW
NEEDLE SHIELD
CATHODE

Fig. 17

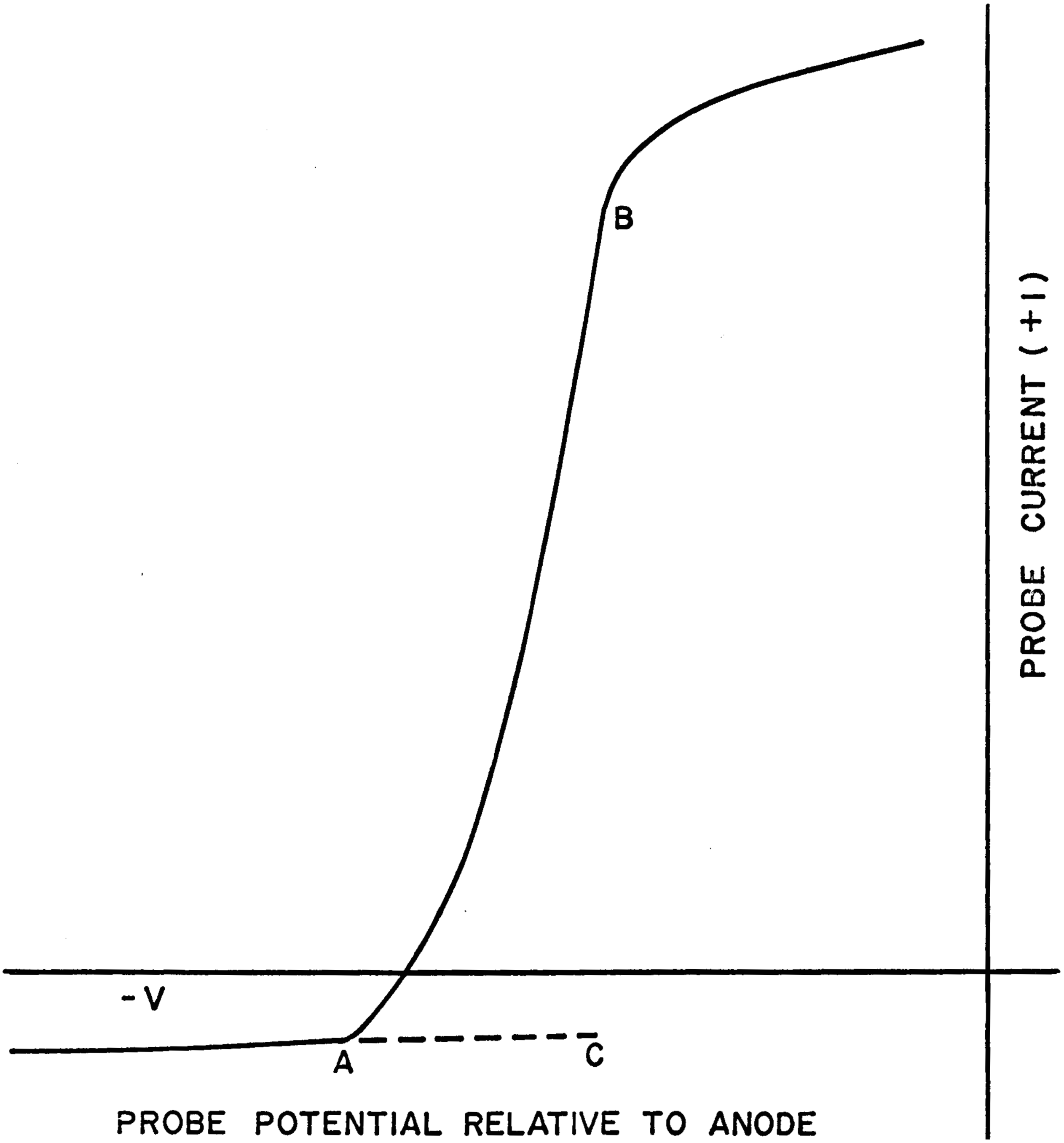


Fig. 18

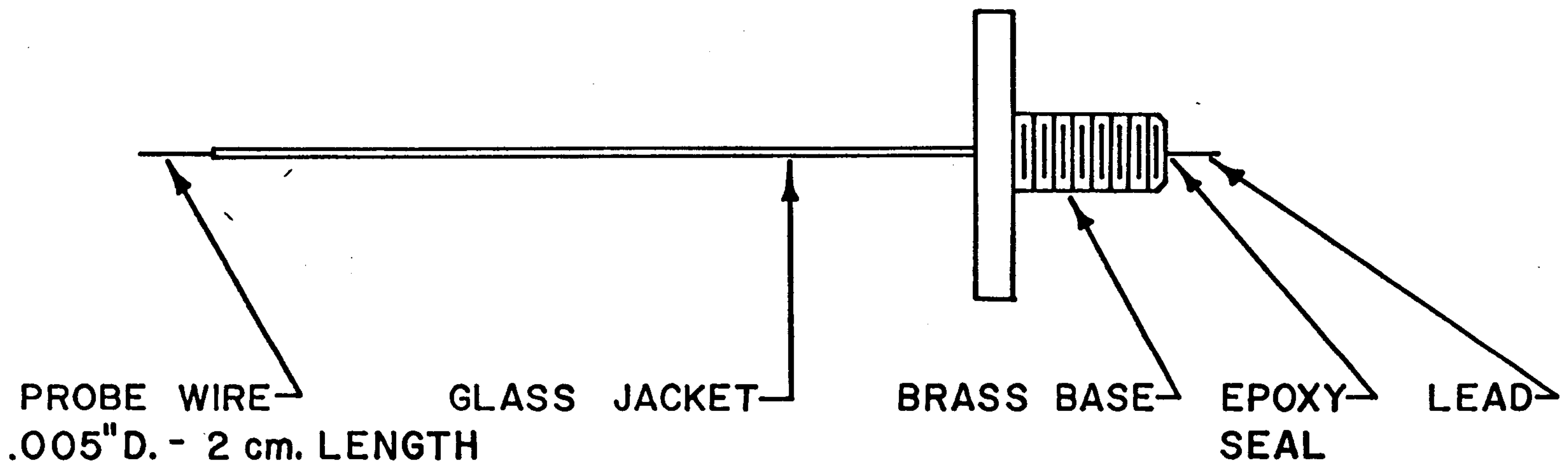
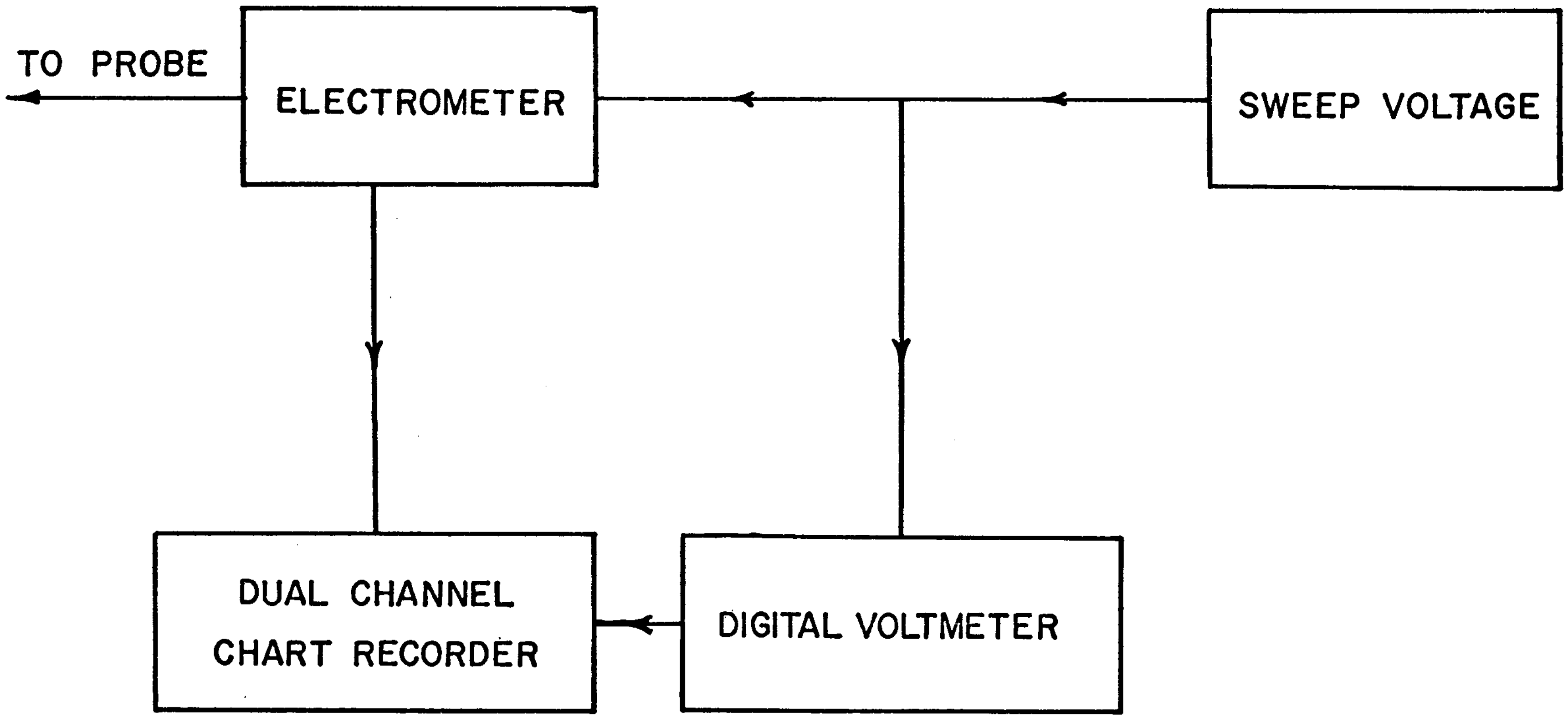

PROBE WIRE
.005"D. - 2 cm. LENGTH
GLASS JACKET
BRASS BASE
EPOXY
SEAL
LEAD

Fig. 19


TO PROBE
ELECTROMETER
SWEEP VOLTAGE
DUAL CHANNEL
CHART RECORDER
DIGITAL VOLTMETER

Fig· 20

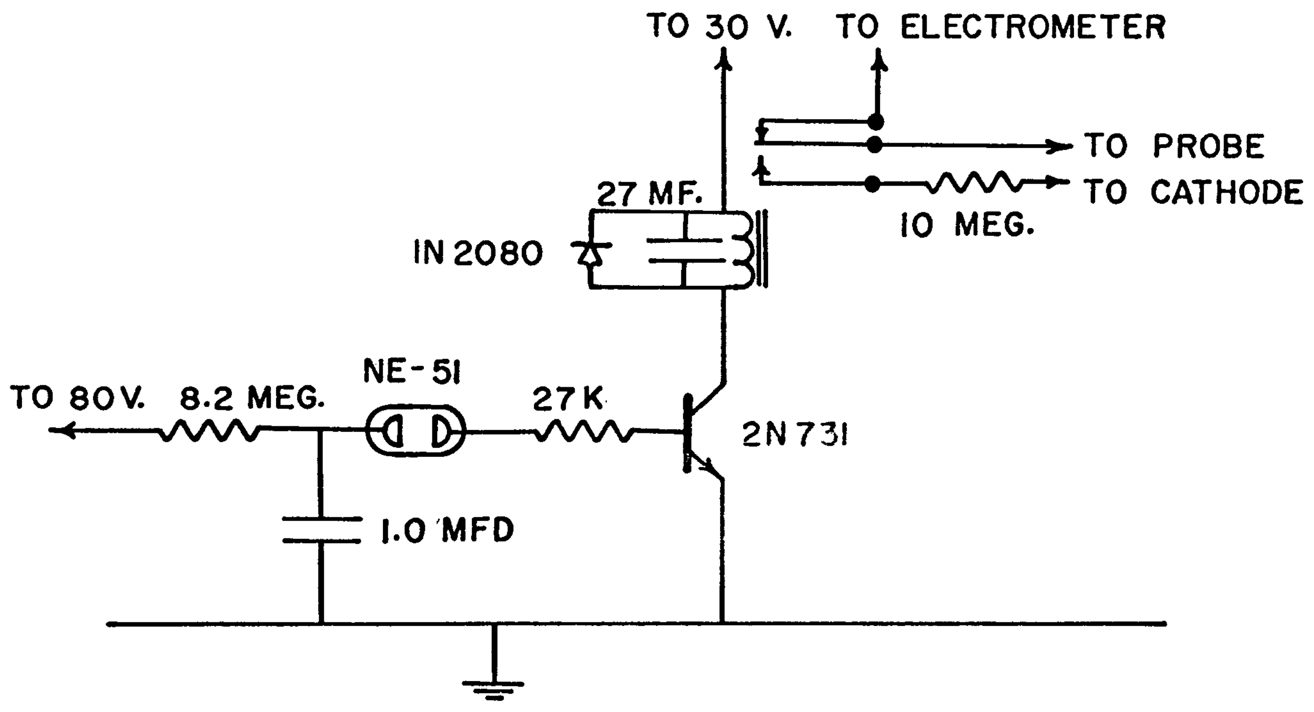

TO 30 V.
TO ELECTROMETER
TO PROBE
TO CATHODE
10 MEG.
27 MF.
IN 2080
NE-51
27 K
2N 731
TO 80V.
8.2 MEG.
1.0 MFD

Fig. 21

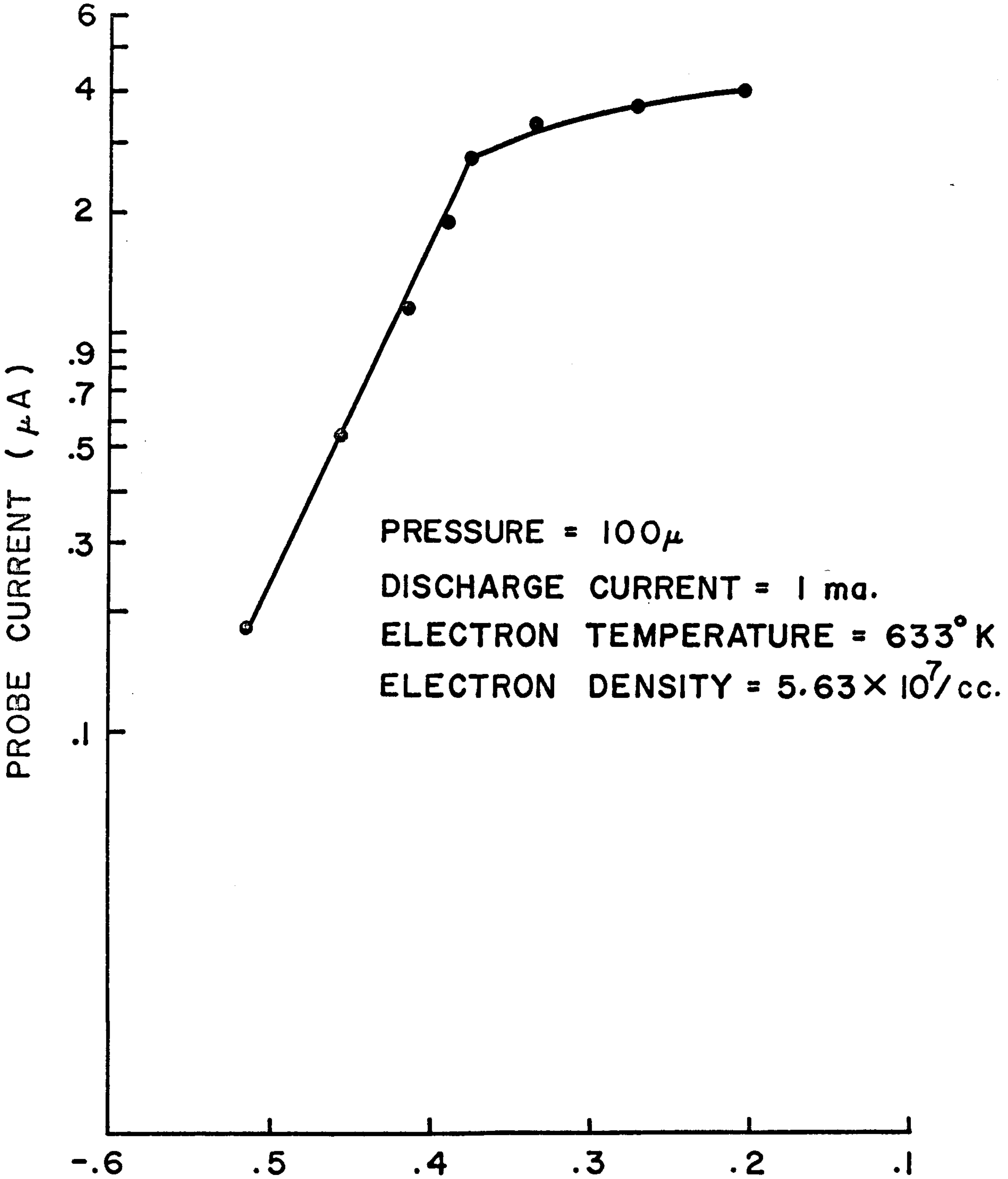

6
4
2
.9
.7
.5
.3
.1
PROBE CURRENT (μA)
-.6
.5
.4
.3
.2
.1
PROBE TO ANODE POTENTIAL (VOLTS)
PRESSURE = 100μ
DISCHARGE CURRENT = 1 ma.
ELECTRON TEMPERATURE = 633° K
ELECTRON DENSITY = 5.63 × 10⁷/cc.

Fig. 22

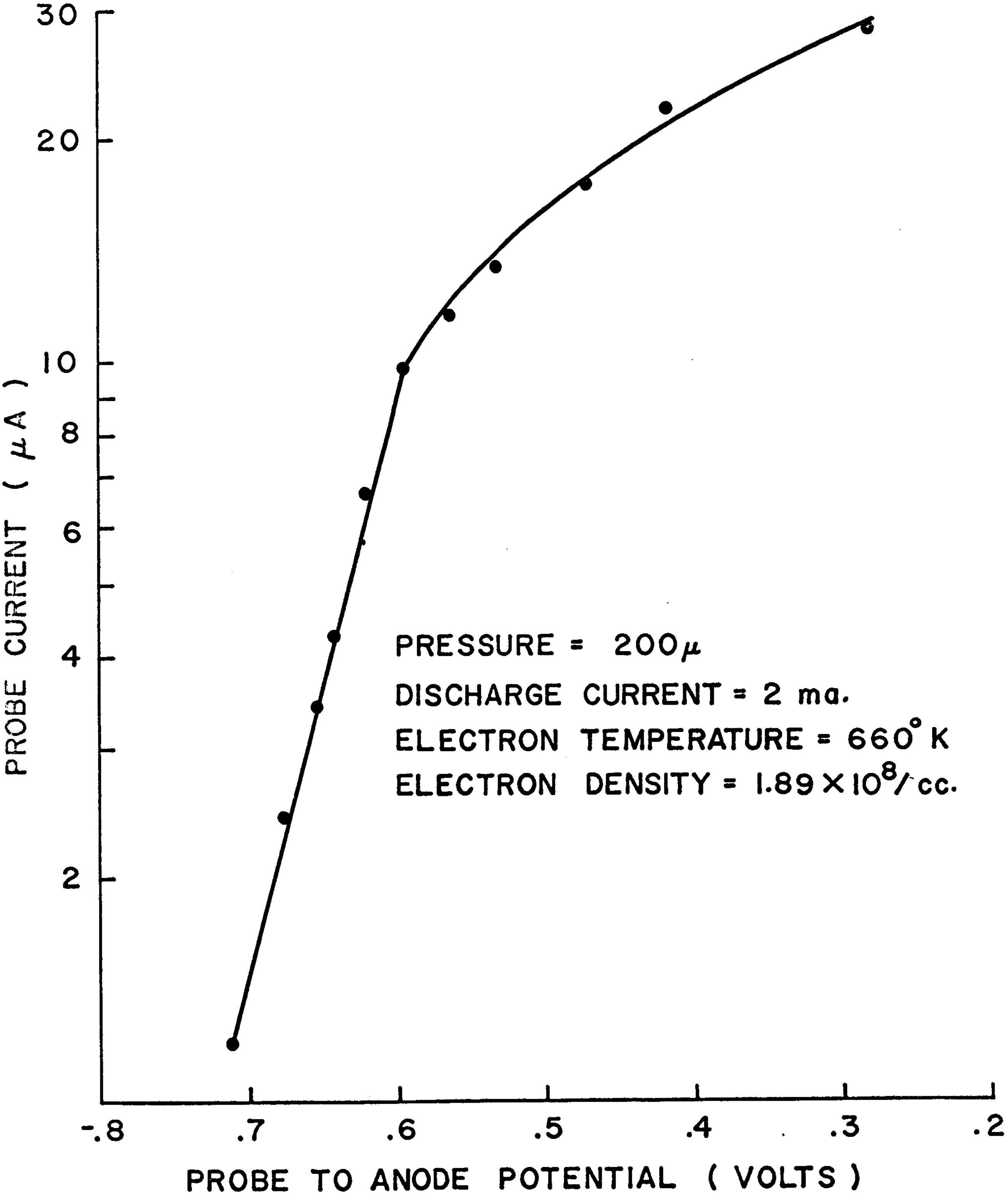

30
20
10
8
6
4
2
PROBE CURRENT (μA)
-.8
.7
.6
.5
.4
.3
.2
PROBE TO ANODE POTENTIAL (VOLTS)
PRESSURE = 200μ
DISCHARGE CURRENT = 2 ma.
ELECTRON TEMPERATURE = 660° K
ELECTRON DENSITY = 1.89 × 10⁸/cc.

Fig. 23

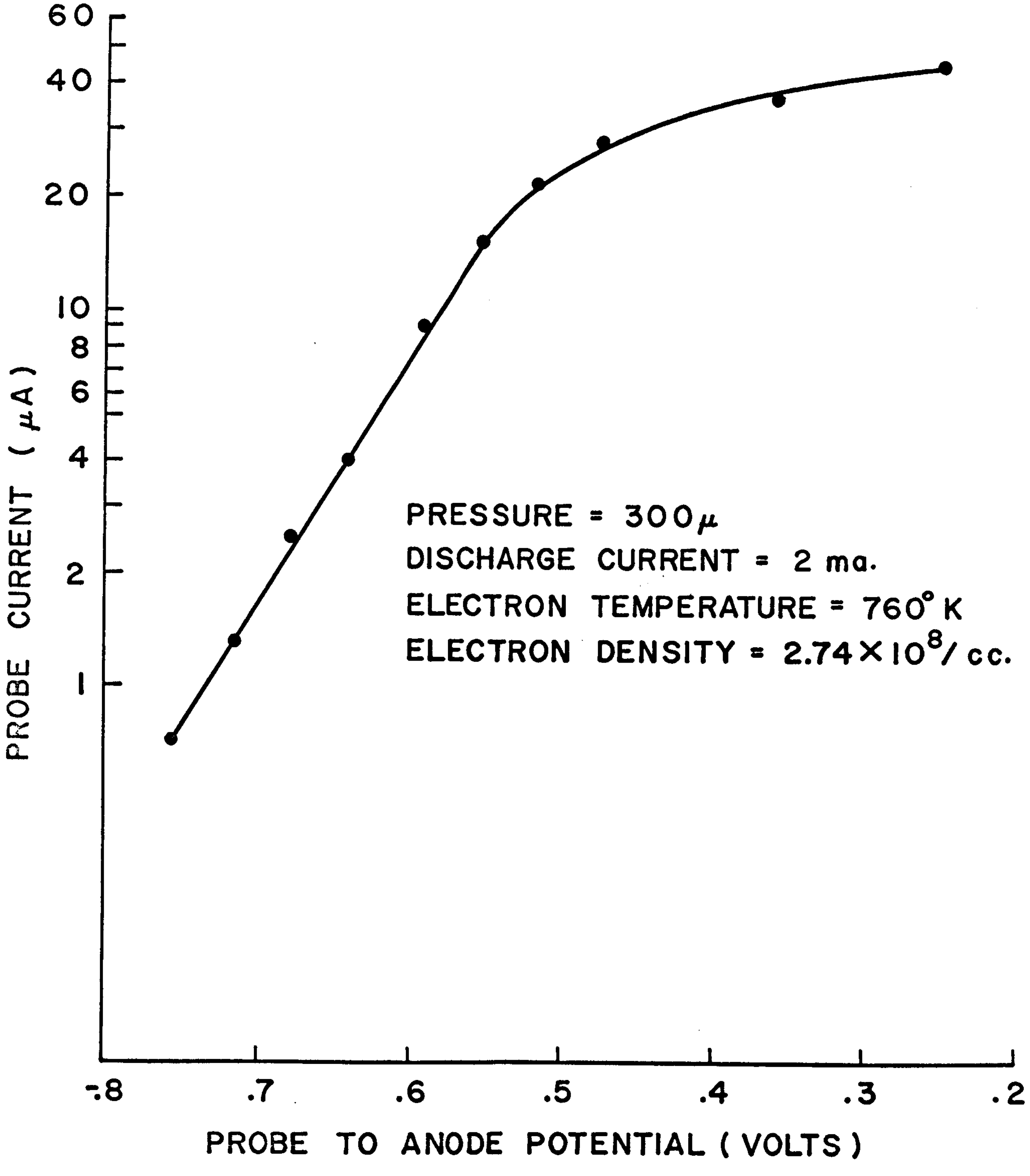

60
40
20
10
8
6
4
2
1
PROBE CURRENT (μA)
PRESSURE = 300μ
DISCHARGE CURRENT = 2 ma.
ELECTRON TEMPERATURE = 760° K
ELECTRON DENSITY = 2.74×10⁸/ cc.
.8
.7
.6
.5
.4
.3
.2
PROBE TO ANODE POTENTIAL (VOLTS)

Fig. 24

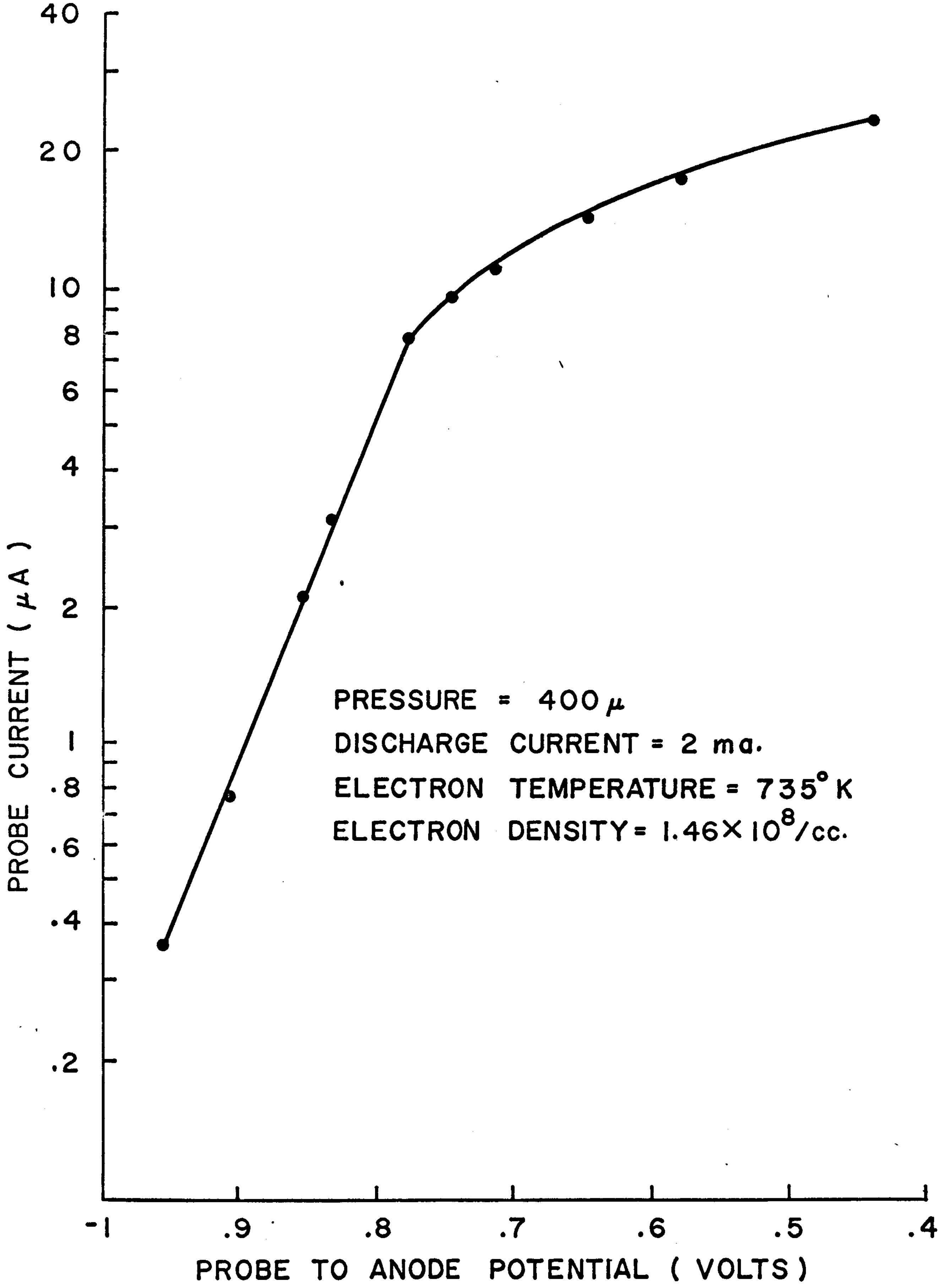
40
20
10
8
6
4
2
1
.8
.6
.4
.2
PROBE CURRENT (μA)
-1
.9
.8
.7
.6
.5
.4
PROBE TO ANODE POTENTIAL (VOLTS)
PRESSURE = 400 μ
DISCHARGE CURRENT = 2 ma.
ELECTRON TEMPERATURE = 735° K
ELECTRON DENSITY = 1.46 × 10^8/cc.

Fig. 25